© Strojniški vestnik 47(2001)8,512-518
ISSN 0039-2480
UDK 536.2
Izvirni znanstveni članek (1.01)

© Journal of Mechanical Engineering 47(2001)8,512-518
ISSN 0039-2480
UDC 536.2
Original scientific paper (1.01)

ENERGY OPTIMIZATION OF THE YANKEE-HOOD DRYER

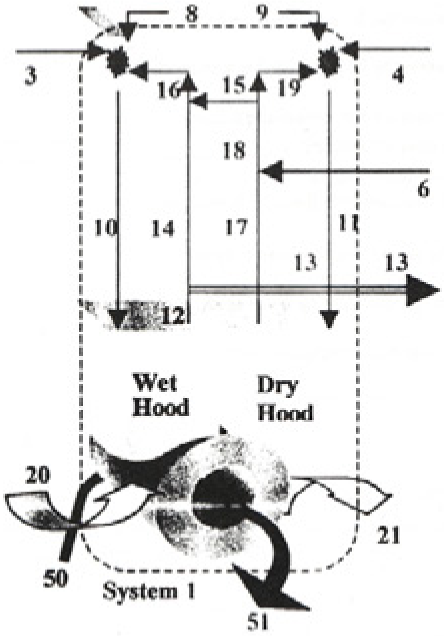
Selis Önel and Güniz Gürüz
Department of Chemical Engineering
Middle East Technical University
Ankara, 06531
Turkey

ABSTRACT

The Yankee-Hood dryer is the crucial section of the paper machine due to the consumption of energy. As a consequence of continuously increasing energy costs, determination of the proper operating conditions is essential to operate the tissue machine in the most efficient and economic means while ensuring paper quality. The objective of this study is to evaluate the Yankee-Hood dryer in 'İpekkağıt' tissue paper factory, set the mass and energy balances and make optimization studies in order to achieve the desired production rate whilst keeping the drying parameters within limits at the minimum energy costs.

The approach to solve the problem is to develop a steady state analytical model. The complicated drying system is simplified as the overall and sub systems. Material and energy balances are set up for each system. Data of machine parameters at several paper grades are collected at the factory during production. Material and energy balance equations are solved with the available data for the unknown parameters and for the determination of the drying parameters most effective on energy consumption. The critical drying parameters are air supply velocity, wet- and dry-hood temperatures, steam pressure in cylinder and exhaust humidity. Efficiency, defined as the ratio of energy required to evaporate the water to energy input through the system boundaries, is calculated as 28-30% for different grades of tissue paper production..

Steady state rate of heat transfer to the wet sheet is analyzed considering the two-way mechanism, from steam through the cast iron shell and from heated air. The transfer of heat is eased in both mechanisms by the lightweight tissue paper that has a comparatively lower internal thermal resistance with respect to other types of paper products. Steam side is modeled considering different thermal resistances in series: Condensate layer, shell, shell-sheet contact, and paper sheet. These resistances are to the same order of magnitude, cast iron shell being the largest and paper sheet the smallest in value. Sheet-shell contact heat transfer coefficient is strongly dependent on sheet moisture content that is assumed to vary almost linearly due to the angular position on the Yankee. Air side heat transfer is mostly affected by the temperature, humidity and velocity of the air that is blown on to the sheet. Calculations resulted out that rate of heat transfer from air side is 55-65% while that from steam side is 35-45% of their total indicating the dominance of air side on drying.



3,4,6: Inlet air 13: Exhaust air 8,9: Natural Gas
20 : Wet paper 21: Dry paper out
50 : Steam 51: Steam and condensate out

Figure 1: System 1, Yankee Dryer and the Hood

MASS BALANCE

System1: Overall System

The overall system involves the Yankee dryer and the hoods with the burners and is presented as System 1 in Figure 1.

Total Mass Balance . Total mass balance is applied on the overall system in order to calculate the rate of net mass transfer. Ranges of all the possible data collected at the factory site, involving eight different products, to be used in the total mass balance are presented in Table 1. Table 2 involves the machine parameters for the specific product and the flow rate of the streams entering and leaving the overall system, System 1. As a result of the total mass balance for Napkin Type-1, it is found out that 979 kilograms of mass is lost by the system per hour.

Water Balance . A large amount of water enters System 1 in wet paper at 60% moisture content. Most of this water is vaporized and removed by the system to reach the desired

Data Collected for the Overall System (System 1)				
Stream #	Stream	Data range	Given in units	Flow rate, kg/hr
3	air in	1.9-2.2	tons/hr	1900-2000
4	air in	3-3.2	tons/hr	3000-3200
6	air in	5-10	tons/hr	5000-10000
8	natural gas in	130-160	Nm^3/min	125-154
9	natural gas in	170-200	Nm^3/min	163-192
13	air out	10-15	tons dry air/hr	14480-21720
		h13=400-500	gr. water/kg dry air	
20	pulp in	VY=1250-1650, VR=1050-1300	m/min	6000-8000
		m21=15-20	gr/m^2	
		w=2.7	m	
		x20=0.60, x21=0.05-0.07		
21	paper out	VY, VR, m21, w		2500-3500
50, 51	steam in, steam and water out	Mms=4000-5000	kg/hr	6000-8000
		Mbt=2000-3000	kg/hr	

Table 1: Total Mass Balance Data for the Overall System (System 1)

Mass Balance Data Collected on the Overall System for Napkin type-1		
Stream #	Flow rate data in given units	Flow rate, kg/hr
3	2.2 tons/hr	2200
4	3.2 tons/hr	3200
6	8.2 tons/hr	8200
8	148 Nm^3/hr	142
9	194 Nm^3/hr	186
13	E13=12.2 tons dry air/hr	17670
	h13=448 gr. water/kg dry air	
20	VY=1500 m/min, VR=1291 m/min	8231
	M21=16.8 gr/m^2	
	w=2.7 m	
	x20=0.60, x21=0.063	
21	VY, VR, m21, w	3514
50	Mms=4542 kg/hr, Mbt=2450 kg/hr	6992
51	Mms, Mbt	6992
Σ streams in	Min	29151
Σ streams out	Mout	28176
Σ out - Σ in	Mi	-979

Table 2: Total Mass Balance Data on the Overall System for a Specific Product

moisture content of the product, usually around 6%. Generally, the wet hood removes 55% of the total amount of water removed out of paper while the dry hood removes the remaining 45%. Table 3 presents the rate of water removal in kilograms per hour basis for a specific product.

Rate of Water Removal (Drying) for a Product		
Product type	Napkin Type-1	Symbol
Pulp fed, kg/hr	8231	M20
Paper produced, kg/hr	3514	M21
Water removed, kg/hr	4717	Wr

Table 3: Water Removed out of Wet Paper per hour during Yankee-Drying

Natural gas is assumed to be dry and pure methane. 100% Conversion takes place due to the single reaction of methane with oxygen. The combustion reaction considered is:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O\,.$$

The amount of water produced at the wet- and dry-burners is referred as the water generated. In general, temperature of the dry side must be slightly higher than the wet side due to the drying requirements. It is more difficult to remove the water out of the wet paper as it gets dried and the water remained is the molecules that have attached to the cellulose fibers (Lehtinen, 1992). Therefore, the amount of fuel fed to the dry side is more than that fed to the wet side thereby causing the generation of more water in the dry hood.

Water Balance on the Overall System (System 1)		
Stream #	Stream	Napkin Type-1
		kg / hr
3	in	3
4	in	4
6	in	10
8	in	0
9	in	0
13	out	5466
20	in	4938
21	out	221
50	in	6992
51	out	6992
Wet side burner	generation	313
Dry side burner	generation	410
Win		11947
Wgen		723
Wout		12679
(Win+Wgen) -Wout		-9

Table 4: Water Balance on theOverall System

Table 4 indicates that fresh air entering in streams 3, 4 and 6 has almost negligible contribution in the overall water balance. Rate of net water transfer through system boundary is 9 kilograms per hour, which is negligible making an order of magnitude comparison.

System 2 and 3: Wet and Dry Sides

The wet and dry section classification has been done by the manufacturer due to the existence of the two hoods and the decreasing moisture content of the paper web as it travels under the hoods. Wet section involves the wet-side burner and the wet hood, represented as System 2 in Figure 2 and dry section involves the dry-side burner and the dry hood, represented as System 3 in Figure 3. Streams and their contents are explained in Table 5.

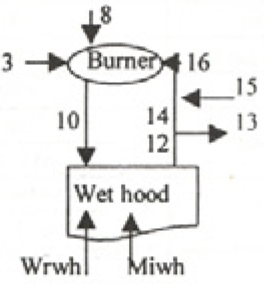


Figure 2: System 2,
Wet side streams

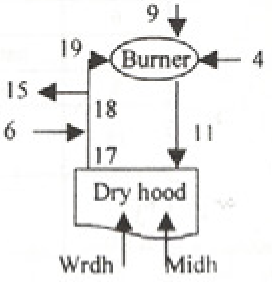


Figure 3: System 3,
Drv side streams

Wet Side and Dry Side Streams (System 2 and 3)		
Stream Explanation	Wet s.	Dry s.
Hot Fresh air	3	4 & 6
Natural Gas	8	9
Heated Blowing air	10	11
Humid air returning from the hoods	12, 14	17
Exhaust humid air	13	--
Transfer air between hoods	15	15
Recycle air feed to the burner	16	19
Rate of net mass tr. through system	Miwh	Midh
Rate of net water tr. (paper to hoods)	Wrwh	Wrdh

Table 5: Explanation of wet and dry side streams

Mass balance sheets for System 2 and System 3 are prepared. Both systems are divided into subsystems around the burner, the hood and the other mixing points. The set of linear equations written for each side are to be solved together to obtain the unknown parameters. As a result of the degrees of freedom analysis on each side, both the wet and dry-side systems are found to be undefined, number of unknown parameters are more than the number of independent equations.

The first set of equations presented in Tables 6 and 7 does not give unique solution. In the second set of equations, an independent equation with a dummy parameter, λw for the wet side and λd for the dry side, is introduced to replace the dependant equation. λw is the mass fraction of stream 13 (exhaust stream) in stream 12 (recycle stream). λd is the mass flow ratio of stream 18 (part of the dry-side recycle stream that is fed with hot fresh air), to stream 19 (final part of the recycle stream that is fed to the burner). The λw and λd values are determined as 0.48 and 0.75 respectively by solving each side using the design values. Results for the unknown mass flow rates are presented in Tables 8 and 9. Solutions of each side are compared for the flow rate of air transfer stream, M15, and for the validity of the mass flow rate of each stream.

Mass Flow Rate Parameters and Equations in the Wet Side Mass Balances			
Known	Unknown	Set of Equations 1	Set of Equations 2: Solution with λw
M3	M10	M10=f(M12,Miwh,Wrwh)	M10=f(M12,Miwh,Wrwh)
M8	M12	M12=f(M13,M14)	M12=f(M13, λw)
M13	M14	M14=f(M15,M16)	M14=f(M12,M13)
Mi	M15	M15=f(M3,M8,M13,Miwh,Wrwh)	M15=f(M14,M16)
	M16	M16=f(M3.M8,M10)	M16=f(M3,M8,M10)
	Miwh	Miwh=f(Mi,α)	Miwh=f(Mi,α)
	Wrwh	Wrwh=f(Wr,β)	Wrwh=f(Wr,β)

Table 6: Wet Side Mass Balance Flow Rate Parameters and Equations

Mass Flow Rate Parameters and Equations in the Dry Side Mass Balances			
Known	Unknown	Set of Equations 1	Set of Equations 2: Solution with λd
M4	M11	M11=f(M17,Midh,Wrdh)	M11=f(M17,Midh.Wrdh)
M6	M15	M15=f(M4,M6,M9,Midh,Wrdh)	M15=f(M18,M19) or M15=f(M4,M6,M9,Midh,Wrdh)
M9	M17	M17=f(M6,M18)	M17=f(M6,M18)
Mi	M18	M18=f(M15,M19)	M18=f(M19, λd)
	M19	M19=f(M4,M9,M11)	M19=f(M4.M9,M11)
	Midh	Midh=f(Mi,α)	Midh=f(Mi,α)
	Wrdh	Wrdh=f(Wr,β)	Wrdh=f(Wr,β)

Table7: Dry Side Mass Balance Flow Rate Parameters and Equations

Mass Flow Rates of the Wet Side Streams, λw=0.48			
Known	kg/hr	Unknown	kg/hr
M3	2200	M10	34700
M8	142	M12	36800
M13	17670	M14	19140
Mi	-979	M15	13220
		M16	32360
		Miwh	-490
		Wrwh	2594

Table 8: Mass flow rates of the wet side streams calculated for λw=0.48 (System 2)

Mass Flow Rates of the Dry Side Streams, λd=0.75			
Known	kg/hr	Unknown	kg/hr
M4	3200	M11	34700
M6	8200	M15	13220
M19	186	M17	44680
Mi	-979	M18	52880
		M19	39660
		Midh	-490
		Wrdh	2123

Table 9: Mass flow rates of the dry side streams calculated for λd=0.75 (System 3)

Hood Operation Depending on Design Values	Wet-Side (mass %)	Dry-Side (mass %)	Total (kg/hr)
Water removed by each hood	55	45	4885
Air infiltration by each hood	50	50	4000
Total infiltration by each hood	53	47	8885

Table 10: Hood operation depending on design values

The hoods not only remove the water in wet paper, but infiltrate air during the suction operation. Fraction of net mass transfer through wet-section boundaries is shown as α and fraction of wet section water removal in total (Wr) is shown as β. Using design data, α and β are found as 0.50 and 0.55. In total, wet hood infiltrates approximately 53% of the mass and dry hood infiltrates the remaining 47%. The percent removal of water, infiltration of air and their total is presented in Table 10.

ENERGY BALANCE

System 1: Overall System

Overall energy balance is applied on the system in Figure 4. The aim is to calculate the rate of net heat transfer Q, energy required to evaporate and remove the water out of the wet paper, and efficiency of the system under the given conditions. The ranges of the available intensive parameter data for the production of several different tissue paper types are presented for each stream in Table 11.

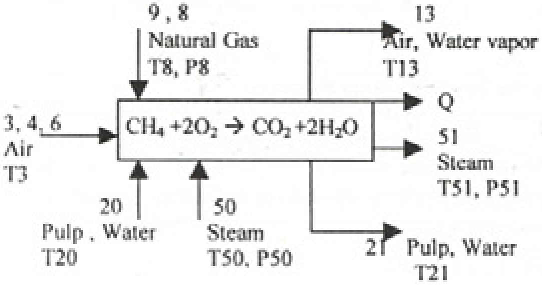


Figure 4: System 1, Overall system (cylinder, hoods, burners)

Wet paper entering Yankee cylinder is assumed to be 30°C and 60% water. Product stream temperature, T21, is constant and around 92°C. Fresh air in streams 3, 4 and 6 is heated up to T3°C at the first heat exchanger before it is fed to the system. Energy generation is due to combustion assumed to be taking place with 100% conversion at the reaction temperature, Trxn.

Data and results of the overall energy balance for a specific product are shown in Table 12. As a result, on the order of 10^6 kilo-joules heat is lost by the system per hour. The rate of heat energy required to evaporate the water in the wet paper at the average paper temperature (T21) is found as $1.074 \cdot 10^7$ kilo-joules per hour for Napkin type-1.

Data Collected for the Overall System (System 1)			
Stream	#	Property	Data Range
Air in	3,4,6	T3=T4=T6	130-160 °C
Natural gas in	8,9	T8=T9, P8=P9	10-35°C, ~1.4 bar
Air out	13	T13	270-290 °C
Wet paper in	20	T20	~30 °C
Dry paper out	21	T21	85-98 °C
Steam in	50	P50	8-9.8 bar
Steam-water out	51	T51	170-180 °C
Combustion	Burners	Trxn	350-460 °C

Table 11: Data for the Overall System (System 1)

Overall Energy Balance for Napkin Type-1 (System 1)				
	Stream #	Temperature (°C)	Pressure (bar)	Heat tr. Rate (kJ / hr)
In	3, 4, 6	273		$1.721 \cdot 10^6$
	8, 9	29.1	1.4	$3.095 \cdot 10^3$
	20	30		$6.451 \cdot 10^5$
	50		9.5	$1.941 \cdot 10^7$
	Total in			$2.178 \cdot 10^7$
Generation	burners	458		$1.645 \cdot 10^7$
Out	13	286		$1.848 \cdot 10^7$
	21	92		$5.006 \cdot 10^5$
	51	177		$1.444 \cdot 10^7$
	Total out			$3.342 \cdot 10^7$
Rate of net heat loss through sys. boundary, Q				$4.807 \cdot 10^6$
Energy required to remove water at T21, Hv				$1.074 \cdot 10^7$
Efficiency				28.1 %

Table 12: Energy Balance on System 1 for a Specific Product

System 4: Paper-Hood Interface

Only the hood and paper is involved in System 4. Energy balance and temperature data sheet is presented in Table 13. Summary of the mass and energy balance results on System 1 and System 2 is shown in Table 14.

Energy Balance at the Shell-Hood Interface (System 4)					
Heat transferred	Stream	Temperature (°C)		Symbol	Heat tr. Rate (kJ/hr)
By entering streams	20	T20	30	H20	6.451E+5
	50	T50	177	H50	1.941E+7
	10	T10	452	H10	3.822E+7
	11	T11	456	H11	3.94E+7
By leaving streams	21	T21	92	H21	5.006E+5
	51	T50	177	H51	1.444E+7
	12	T12	337	H12	3.831E+7
	17	T17	365	H17	3.621E+7
By net mass transferred	Miwh	T10	452	HMiwh	-2.187E+5
	Midh	T11	456	HMidh	-2.208E+5
Rate of net heat tr. through sys. boun.				Q	-7.774E+6

Table 13: Data and Energy Balance at Paper and Hood Interface (System 4)

Comparison of Systems 1 and 4		
Rate of net transfer through system boundary (Napkin Type-1)		
System	Heat (kJ/hr)	Mass (kg/hr)
System 4:Cylinder+hood+burners	-4.807E+6	-979.422
System 5:Cylinder-hood interface	-7.774E+6	-976.989

Table 14: Comparison of the Energy and Mass Balance Results for Systems 1 and 4

Table 14 indicates that, rate of net mass transfer in both systems is almost the same meaning that net mass transfer is mainly controlled at the paper surface-hood interface. Rate of net heat transfer is to the same order of magnitude in both systems. It is greater for System 4 due to the lower temperature reading of the recycle streams 12 and 17and higher reading of the blowing streams. Since the pipe lines transferring air are long, there is temperature variation along the line.

Heat Transfer Between Steam and Web

Transfer of heat to paper by two mechanisms, conduction from steam and convection from air, is represented in Figure 5. Resistances in series are condensate, shell, shell-paper interface, and paper (Chance,1989). The effect of each thermal resistance on the overall heat transfer is to be determined. Heat transfer between these layers significantly affects overall drying rate.

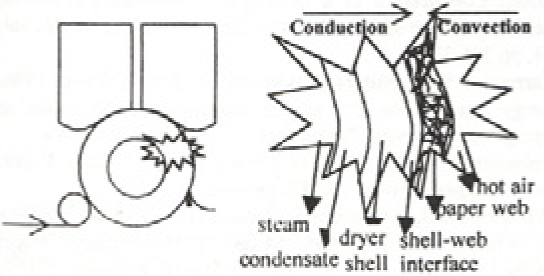


Figure 5: Thermal resistances and the two-way heat transfer

Paper sheet sticks on the Yankee cylinder at θ=0° and wraps 314° as shown in Figure 6. Hood region starts at θ=22° and dry hood starts at 164°. Totally the hood wraps 257°.

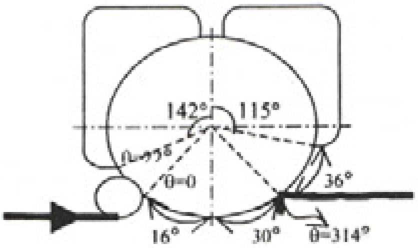


Figure 6: Angular View of the Yankee Cylinder

Paper is assumed thin enough that temperature and moisture content variation in thickness direction is unimportant (Karlsson and Heikkila, 1987). Circumferential sheet temperature increases in machine direction. but it is assumed to be uniform (Ahrens, 1995). Moisture profile is plotted assuming it decreases linearly with wrap angle θ (MC(θ)) in the hood region as paper gets dry (Lindeborg, 1982; Ahrens, 1995). Heat transfer coefficient of shell-web interface, is a function of moisture content:

$$\mathrm{hint}(\theta) = \alpha + \beta \cdot \frac{\mathrm{MC}(\theta)}{1 - \mathrm{MC}(\theta)} \qquad (1)$$

α and β are 198.7 and 4542 W/m²K respectively (Ahrens, 1995). Paper conductivity, kp(θ) is assumed to change linearly between 0.216 and 0.144 due to Han's calculations for tissue paper (Seyed-Yagoobi et al., 1992). Steam condensing heat transfer coefficient, hcond, is determined approximately considering the rimming condition due to high speeds of the Yankee cylinder, 1200-1700 m/min and the respective values found in literature (Wilhemsson et al., 1996; Ahrens, 1995, Appel & Hong, 1969). Blowing air heat transfer coefficient, ha, is assumed to be constant and 227.1 W/m²K (Ahrens, 1995) due to the fact that it is 25-250 W/m²K for gases in forced convection (Incropera & De Witt, 1990). Figure 7 and Table 15 indicate that dryer shell is the largest and paper web is the smallest resistance to heat transfer. Overall thermal resistance for conduction, R, is calculated as a function of the wrap angle using the equation for resistances in series:

$$R(\theta) = R1 + R2 + R3(\theta) + R4(\theta) \qquad (2)$$

The conduction of heat from steam to paper (Qstp) and the convection of heat from air to paper (Qap) are calculated as point values at each angle on the paper sheet. The total amount of heat supplied by both mechanisms is calculated by taking the sum over the wrap angle ranges specified in Table 16.

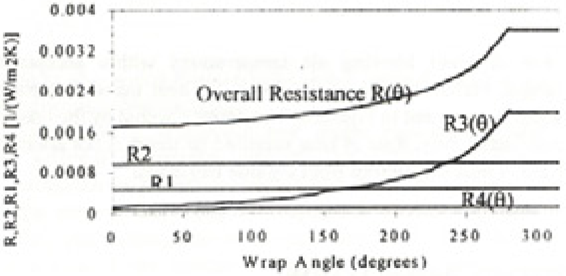


Figure 7: Thermal Resistances versus Wrap Angle

Thermal Resistances Affecting Overall Heat Tr. Rate							
Conduction Convection	Thick. (mm)	Heat Tr. Coef.	Ther. Resistivity (W/m²K)*10⁴				
			Wrap-angle, θ degrees				
			θ	22	164	279
Steam-cond.	4-8	hcond	R1	5.0	5.0	5.0
Dryer shell	48.6	kshell	R2	9.8	9.8	9.8
Shell-web		hint(θ)	R3(θ)	1.5	4.6	19.4
Paper web	0.02	kp(θ)	R4(θ)	0.9	1.1	1.3
Blowing Air		ha	1/ ha	44.0	44.0	44.0

Table 15: Conduction and Convection Resistances

Effects of Conduction and Convection for Napkin Type-1			
Heat Transfer Direction	Wrap Angle (θ degrees)	Symbol	Heat given (kJ/hr)
from air to paper	22→279	Qap	$8.129 \cdot 10^6$
from steam to paper	0→314	Qstp	$4.816 \cdot 10^6$
from steam to cylinder	314→360	Qstc	$0.325 \cdot 10^6$
Heat transferred to paper (Qap+Qstp)		Qp	$1.295 \cdot 10^7$
Heat required to vaporize water (Wr)		Hv	$1.074 \cdot 10^6$

Table 16: Effects of Conduction and Convection on Drying

The results presented in Table 16 indicate that 6% of the heat supplied by steam (2.5% of the total heat) is lost through the uncovered bottom part, 46°, of the cylinder. 62.8% of the heat given to paper is from air while 37.2% is from steam. Steam and air contribution in the total heat supplied is 36.3% and 61.2% respectively.

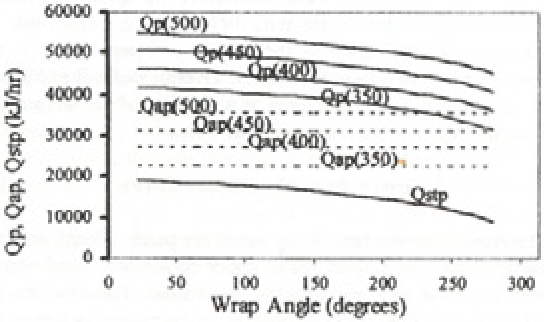


Figure 8: Heat Transfer Rate Point Values vs Wrap Angle (22° to 279°) at Blowing Air Temperatures 350, 400, 450, 500 ° C

For different blowing air temperatures within acceptable ranges, variation of the point values of heat transfer to paper sheet is presented in Figure 8. The points covered by the hood is considered only. Rate of heat supplied by steam is not affected. Rate of heat transferred from air side increases.

ENERGY OPTIMIZATION

The same final product can be produced by changing different drying parameters and keeping the rate of paper production constant. With reference from literature, the most effective drying parameters are the air supply velocity in each end of air cap (blowing air velocity), hood temperatures, steam pressure in cylinder and exhaust air humidity (Tarnawski et al., 1996; Schukow et al., 1988; Toivonen,1982). Total energy, ET, can be written as a function of the drying parameters:

$$ET = f1(\text{blow vel.}) + f2(\text{steam P}) + f3(\text{air T, exhaust hum}) \quad (3)$$

Energy consumption is from three different sources used in the system: Natural gas, steam and electricity. Gas consumption is a function of the blowing air temperature and exhaust humidity. Steam consumption is a function of the steam pressure in the cylinder. Electricity consumption is a function of the blowing air velocity. Contribution of gas in the total energy use is more. In general, energy from gas is about 50-60%, energy from steam is 40-50%, and energy from electricity is 5-10% of the total consumption.

REFERENCES

Ahrens F.W., 1995, Effect of Shell Thermal Dynamics on Predictions of a Yankee Dryer Model, *ASME Heat Transfer Division*, vol. HTD 317-2, pp. 427-435.

Appel D.W. & Hong S.H., 1969, Condensate Distribution and Its Effects on Heat Transfer in Steam-Heated Dryers, *Pulp Paper Magazine Canada*, vol. 70, p 66.

Chance J.L., 1989, Overview of the Dryer Section, *Tappi Seminar Notes: Practical Aspects of Pressing and Drying*, Atlanta, USA, vol 62, pp. 121-137.

Incropera, F.P. & De Witt, D.P., 1990, *Fundamentals of Heat and Mass Transfer*, p. 9, John Wiley & Sons, Singapore.

Karlsson, M. & Heikkila, P., 1987, Computer Simulation of Yankee Drying, *Drying '87*, A.S. Mujumdar, Ed., Hemisphere, Washington, pp. 194-202.

Lehtinen J., 1992, The Heat Pipe Process in Intraweb Heat Transfer in Hot Surface Paper Drying, *Paperi ja Puu-Paper and Timber*, vol. 74, pp. 560-571.

Lindeborg C., 1982, A Method for Analysis of Cross-Direction Drying Performance in a Paper Machine, *TAPPI Journal*, vol. 65, pp. 119-122.

Schukow V. & Heberl A., 1988, Humidity and its Effect on Thermal Efficiency of Yankee Hoods, *Tappi Journal*, vol. 71, pp. 68-70.

Seyed-Yagoobi J., Ng K.H., Fletcher L.S., 1992, Thermal Contact Conductance of a Bone-Dry Paper Handsheet/Metal Interface, *Journal of Heat Transfer, Transactions of ASME*, vol. 114, pp 326-330.

Tarnawski W.Z., Mitera J., Borowski P., Klepaczka A., 1996, Energy Analysis on Use of Air and Superheated Steam as Drying Media, *Drying Technology*, vol.14, pp. 1733-1749.

Toivonen K., 1982, Yankee Drying of Soft Tissue Paper, *Svensk Papperstidning*, vol. 85, pp. R107-R114.

Wilhemsson B., Stenstrom S., Nilsson L., Krook R., Persson H., Wimmerstedt R., 1996, Modeling Multicylinder Paper Drying – Validation of a New Simulation Program, *TAPPI Journal*, vol. 79, pp. 157-167.