ANALYSIS OF THE HEAT DEMAND IN BATCH KILNS

Jan-Olof **Anderson**
Luleå University of Technology, Division of Energy Science
9718 87 Luleå– Sweden
Jan-Olof.Anderson@ltu.se

Lars **Westerlund**
Luleå University of Technology, Division of Energy Science
9718 87 Luleå– Sweden
Lars.Weterlund@ltu.se

Abstract

During the production of lumber more than half of the entering timber to the sawmill becomes biomass. About 12 %wt of the entering timber is combusted to supply heat for the sawmill. Major part of the heat is supply the kilns. Due to the high evacuation losses the energy efficiency in a traditional drying kiln is only 13 %. This makes the lumber drying to a low and ineffective process in an energy point of view.

Forced drying technologies are a compromise between high lumber quality, low lead time and decreased energy use. Often is the quality and lead time prioritised. This paper advises an appropriate method to simulate the energy efficiency when drying lumber in a batch kiln. To ensure real life drying conditions, with sufficient quality and lead time the initial conditions were made from simulated drying schemes, from simulation program called Torksim. By combine thermodynamics and psychrometric relationship, the energy streams and losses during the drying scheme were established. The program can be used to compare several drying conditions and clarify the magnitude of losses. Different types of technologies affecting the kiln energy efficiency and to compare drying conditions to each other. For instance heat exchanger, heat pumps, condense walls, absorption system etc.

The used drying conditions are suitable for north European lumber and climate, but the initial conditions can be changed for analyses of other types of drying conditions. The program is a usable tool to analyses different types of technologies effect on the kiln energy efficiency and to compare drying conditions and different drying scheme to each other.

Key words: Wood drying, Bioenergy, Drying technology, Energy efficiency, Sawmill

Introduction

When producing lumber the sawn timbers need to be dried to obtain sufficient quality, with less lumber deformation and unwanted moisture content. To decrease the leading time the drying process is done under force convection techniques, with drying facilities called drying kilns. The drying process is still the most time and heat consuming process at sawmills (Anderson, J-O, 2011).

The low lumber interchange at sawmills has resulted in a large amount of excess biomass from the sawing, sorting, barking and planning processes (Staland. J, 2000). A significant part of biomass is used to supply heat to the drying. (Esping. B, 2000). This is often done within own firing furnace, otherwise the heat is bought from nearby industries. Annually in Sweden 18 Mm^3 (Nylinder. M, 2009) lumbers are produced, which corresponds to a national heat consumption of 4.9 TWh (Anderson, J-O 2011). The heat recycling in the kilns is quite uncommon. In the few cases the heat is recycled with the air/air heat exchanger (Esping. B, 1996).

When producing lumber is the lead time and wood quality prioritized before the energy consumption. The historical low energy and biomass prices have prepossess lower concern about the energy efficiency among the industry. Software has been developed to ensure correct kiln air conditions in order to attain adequate lumber quality [3-5]. The research devoted to increased energy efficiency for lumber drying have been low prioritized for the past decades, due to the large supply of biomass at sawmills and the historical low biomass prices. Several experimental measurements, since the 70th, have been established at different drying conditions to evaluate the energy consumption (Esping. B, 1996, Tronstad. S, 1993, Stridberg. S, 1985). This method is very time consuming and costly. Instead, a software can be used to analyse the energy consumption, different energy streams and air conditions regarding to each specific drying condition based on each sawmill qualification and can then be implemented.

To ensure realistic drying conditions and high lumber quality a kiln scheme program, named Torksim, was used (Salin, J-G, 1990, Salin, J-G, 2008). Torksim is developed by Technical Research Institute of Sweden, SP. It is mostly used by sawmills and it is employed to predict the drying scheme, to obtain a specific lumber moisture content with a secured lumber quality and lead time, for the specific drying conditions. An analytical calculation program was constructed in IGOR (a commercial available software), with the drying cycle from Torksim used as boundary conditions. With thermodynamic and psychometric relationship implemented could each specific energy flows and losses be established over time, to analyse the kiln energy efficiency. An implementation has been done to analyse different technologies affect at the overall dryer energy efficiency. With this program, it is possible to compare different technologies which can increase the energy efficiency under different drying and lumber conditions.

Drying climate

The common types of wood driers are the batch and the progressive kiln (Staland. J, 2002). They operate by replacing the humidified air with dryer and cold outside air; these are the oldest and the most commonly used method. The low energy content in the outdoor air needs to be increased to the drying conditions, which results in a large heat demand. The kiln climate is controlled with dry and wet bulb temperature inside the kiln. The main difference between these kiln types is that the air states inside the batch kiln changes over time compared to a progressive kiln the air state remain the same over time. A progressive kiln works instead with several air zones separated to each other.

An example of drying cycle of air is illustrated in Figure 3. The process starts from the intake air, from outside air conditions (1), the air is then heated with a heating battery between point (2) and (3) as the same time the air is circulated with a circulation fan from one side of the lumber package (3), to the other side (4). Finally, a part flow of the humidified circulation air is exchanged with dryer outside air, to maintain a high moisture absorbing effect of the air.

A drying scheme is a compromise between increased lumber quality, decreased lead-time and if possible, decreased heat consumption. Sufficient quality and less lead-time have often higher priority than the energy efficiency. An example of the in temperature and lumber moisture over time is shown in Figure 1.

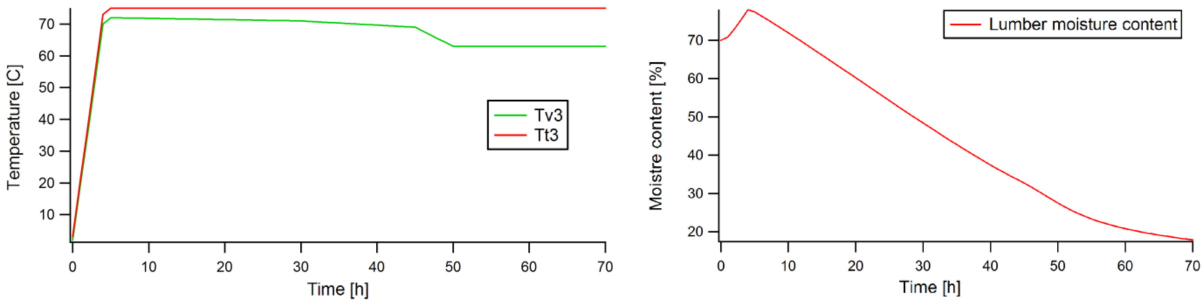

FIGURE 1. AIR STATE OVER TIME

Methodology

Model description

This model is divided into four different parts. Part a, The specific drying conditions were implemented as initial boundary conditions to Torksim, see Table 1. Due to the sawmills` high priority of sufficient quality and low lead-time, simulation of the drying climate should be operated accordant to real life quality and lead-time requirement.

To receive these requirements the drying schemes were established through a drying simulation program, Torksim (Salin, J-G, 1990, Salin, J-G, 2008), this step is numbering b in Figure 2.

The drying scheme provides the lumber moisture content, dry and wet bulb temperature, the relative pressure for each drying hour. An example of this is shown in Figure 1. This is done to achieve a realistic drying schedule to apply in the energy calculations. With wanted end moisture content and acquire sufficient quality. c. Program part I (idealic drying conditions) and Program part II (Non- idealic drying conditions). These model parts is schematically shown in Figure 2. Each different steps is explained in the following section, Theoretical model programmed in IGOR

TABLE 1 - INITIAL BOUNDARY CONDITIONS

Type		Magnitude	Unit
Type of dryer		Batch kiln	
Dryer dimension		16x6x8	m
Wood volume in dyer	V_{wood}	150	m^3
Maximum relative pressure		30	%
Type of tree		Pine	
Start moisture content	u_{start}	70	%
End moisture content	u_{end}	18	%
Lumber dimension		50x150	mm
Wood density	ρ	430	Kg / m^3
Kärnveds andel		63,2	%
Drying time	t	70	h

This drying scheme is then implemented as into the constructed calculation program in IGOR, numbered D in Figure 2. With thermodynamic and psychometric relationship implemented specific energy flows and losses could be established over time in order to analyse the kiln energy efficiency.

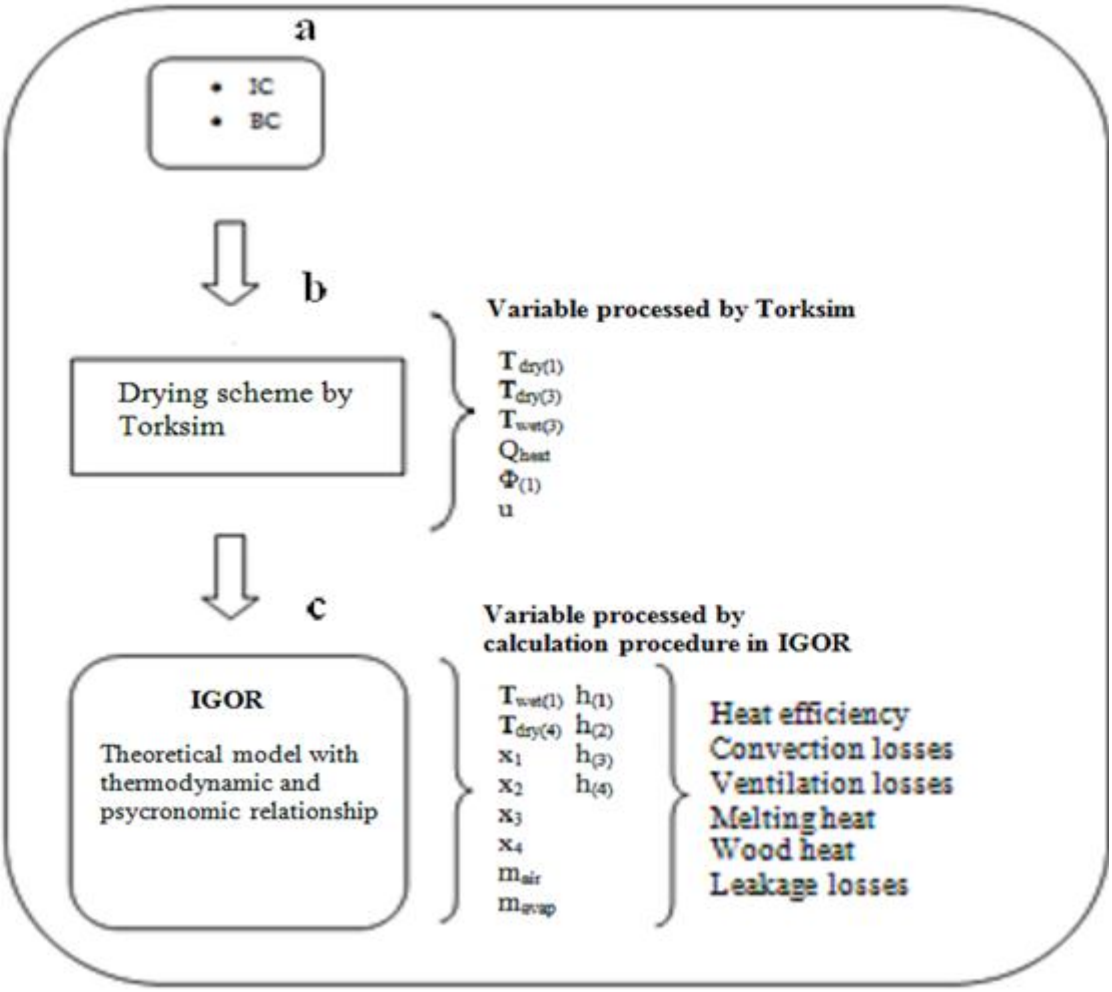

FIGURE 2 - SCHEMATIC REPRESENTATION OF THE MODEL DESCRIPTION

Theoretical model programmed in IGOR

The variable supplied by Torksim, is not enough to establish each air state in the drying cycle, the heat flows, losses, energy efficiency for the drying process. Therefore, additional variables are needed to be calculated, such as; dry bulb temperature in point (3b) and (4), absolute air humidity and enthalpy from point (1)-(4) and mass flow of circulation air, shown in Figure 3. This is made in the Program part I(idealic drying conditions), marked c in the Figure 2. When the ideally drying cycle is provided from Torksim can the air state from point (1) to (4), be calculated with an adiabatic point of view through psycronomic relationships.

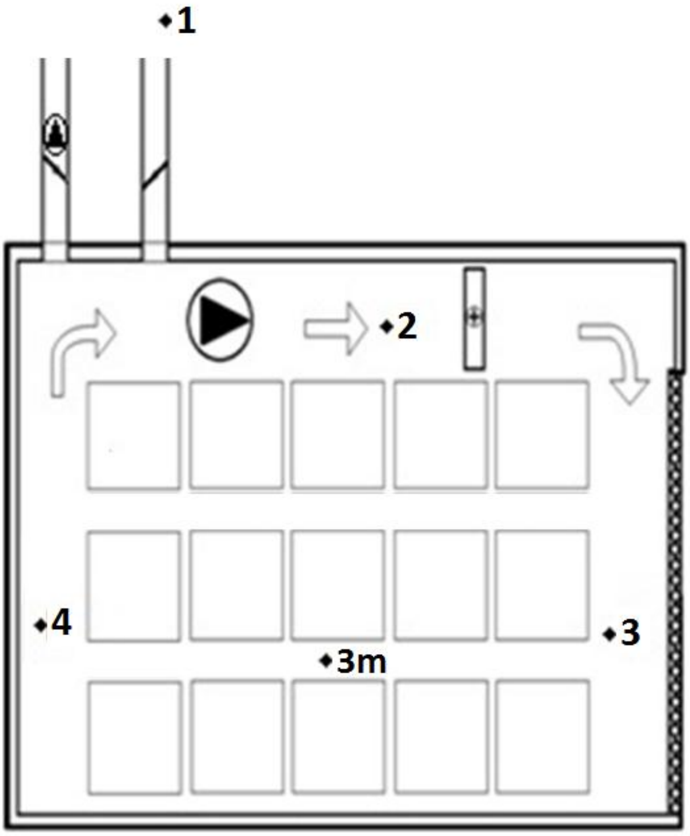

FIGURE 3 - ONE DRYING CYCLE OF CIRCULATION AIR.

Torksim is given the air state in point 1, 3_m and the lumber moisture content over time. The air state in all points, in Figure 3, needs to be determined. The first step is to calculate the air state in point 1. The first step is to calculate the air state in point 1.

The partial water pressure is defined with Eq. 1, the saturation pressure for the dry bulb temperature can be calculated through a polynomial equation.

$$P_w = (\theta/100)P_{s,dry} \qquad \text{(Eq. 1)}$$

The absolute humidity in the air can be calculated through Eq. 2, hence the partial water pressure and the absolute pressure are known.

$$x = 0.622P_w/(P_{tot} - P_w) \qquad \text{(Eq. 2)}$$

The enthalpy can be calculated through Eq. 3 when the temperature and the absolute humidity are known in the calculated point.

$$h = 1.007 * T_d + x * (r + (C_{p,v} * T_d) \qquad \text{(Eq. 3)}$$

The outdoor air state, point 1, in now defined. With the dry and wet bulb temperature known in point 3m the enthalpy can be determined through Eq. 3 and the absolute moisture content can be calculated with Eq. 4 and 5.

$$x_{wet} = 0.622 * P_{s,w}/\left(P_{tot} - P_{s,w}\right) \qquad \text{(Eq. 4)}$$

$x = \left(C_{p,d} * (T_w - T_d) + x_{wet} * r\right) / \left(r + C_{p,v} * T_d - Cp_w * T_w\right)$ (Eq. 5)

The air state in point 1 and 3_m is now defined. But to analyse the energy efficiency and losses the air state in the other points needs to be known. Between point 3 and 4 is the air state only affected by absorption of moisture from the lumber.

The mass of evaporated water to the circulation air can be calculated by considered the decreased wood moisture content over time and the air state in point 3_m by using Eq. 6.

$\dot{m}_{evap} = V_{wood} * \rho * (u_{t-1} - u_t)$ (Eq. 6)

By implement an mass flow rate of the circulation air, valid for these type of drying conditions, Eq. 8 – 10 can be used to determine the absolute moisture content in point 3 and 4.

$x_{diff} = \dot{m}_{evap} / (3600 \dot{m}_{air})$ (Eq. 8)

$x_3 = x_{3m} - x_{diff}/2$ (Eq. 9)

$x_4 = x_{3m} + x_{diff}/2$ (Eq. 10)

The enthalpy in point 3 and 4 can be defined with Eq. 11 and 12.

$h_{3,b} = h_3 - \left(Cp_w * T_w * \dot{m}_{evap} / (3600 * 2\dot{m}_{air})\right)$ (Eq. 11)

$h_4 = h_3 + \left(Cp_w * T_w * \dot{m}_{evap} / (3600 * 2\dot{m}_{air})\right)$ (Eq. 12)

An test is now implemented to ensure that the conditions in point 4 do not exceed saturation conditions. This is done by calculate the absolute moisture content in point 4 if it would be at the saturated point with a polynomial, $x_4 = f(h_4)$, se Eq. 13.

$x_{4\_test} = -2{,}06745 * 10^{-17} * {h_4}^5 + 9{,}60207 * 10^{-14} * {h_4}^4 - 1{,}72423 * 10^{-10} * {h_4}^3 + 1{,}52956 * 10^{-7} * {h_4}^2 + 2{,}99162 * 10^{-4} * h_4 - 4{,}23359 * 10^{-3}$ (Eq. 13)

The absolute moisture content, x_4, determined by Eq. 10 is then compared with the absolute moisture content at the saturation point, x_{4_test}, determined by Eq. 13. If the absolute moisture content is lower than the absolute moisture content at the saturated point, x_{4test}, is x_4 and x_3 valid. Otherwise the absolute moisture content is recalculated though Eq. 14 and 15.

$x_{4`} = x_{4,test}$ (Eq. 14)

$x_{3`} = x_{4,test} - x_{diff}$ (Eq. 15)

The saturated water vapour pressure, Ps_{dry}, can be calculated by a polynomial and the real water pressure Pv_{dry} can be determined through Eq. 16.

$$Pv_{dry} = x_{3m} * P_{tot}/(0.622 + x_{3m}) \qquad \text{(Eq. 16)}$$

The relative moisture content can be determined through Eq. 17

$$\theta = 100 * Pv_{dry}/Ps_{dry} \qquad \text{(Eq. 17)}$$

The absolute moisture content between point 2 and 3 is the same, hence the air is only influenced by heating from the heating battery, Eq. 18.

$$x_2 = x_3 \qquad \text{(Eq. 18)}$$

With the enthalpy, absolute moisture content can the dry temperature be defined through Eq. 19 and Eq. 20.

$$Tt_{3b} = \left(h_{3,b} - r * x_{3,b}\right)/\left(Cp_w + C_{p,v} * x_{3b}\right) \qquad \text{(Eq. 19)}$$

$$Tt_4 = (h_4 - r * x_4)/\left(Cp_w + C_{p,v} * x_4\right) \qquad \text{(Eq. 20)}$$

With known absolute moisture content in point 1, 2, 4 and a mass balance mixing constant, Eq. 21, i.e. how much air is entering the kiln in relation to the circulation air.

$$L_1 = (x_4 - x_2)/(x_4 - x_1) \qquad \text{(Eq. 21)}$$

The enthalpy in point 2 can be defined through Eq. 22 when the mixing relationship is known.

$$h_2 = L_1 * h_1 + (1 - L_1) * h_4 \qquad \text{(Eq. 22)}$$

The dry bulb temperature can be defined through Eq.23.

$$T_{d,2} = (h_2 - r * x_2)/\left(Cp_w + C_{p,v} * x_2\right) \qquad \text{(Eq. 23)}$$

The adiabatically heat consumption is then given by Eq. 25.

$$Q_{heat'} = m_{air'}(h_3 - h_2) \qquad \text{(Eq. 25)}$$

With the air states, magnitude of circulation air and air exchanges rate are known, the magnitude of the losses can be calculated through thermodynamic relationship, as explained below. The losses due to the drying process can be divided into the following parts: transmission losses through walls, $\dot{q}_{wall}$, roof , $\dot{q}_{roof}$, and floor , $\dot{q}_{floor}$, see Eq. 26 - 28, respectively. The total transmission losses are the sum of these losses, Eq. 29. The ventilation losses, $\dot{q}_{vent}$, can be calculated with Eq. 30. The ventilation losses arise, when the moisture air needs to be exchanged with dryer outside air, between points (4), (1) and (2) in Figure 3. Melting heat, $\dot{q}_{melt\ heat}$, and wood heat, $\dot{q}_{wood\ heat}$, are the useful heat for drying the wood, they can be calculated with Eq. 31 and 32. Melt heat, arise if the lumber needs to be heated to 0 ˚C in the beginning of the drying scheme, which only occurs if the lumber has been stored in degrees below zero before the drying process. Wood heat, is the heat that increases the temperature of the wood towards the drying temperature. The Wood heat, has a relationship with the moisture content of the wood, temperature and the specific heat of the water and the wood, see Eq. 32. The specific heat of dry wood can be obtained from Eq. 33 (Dunlop, F, 1912). The leakage losses, $q_{leakage,}$ are control by the leakage factor constant, ɣ, chosen by the user, Eq. 34. The leakage losses mainly arise when the kiln is open during lumber loading and it is typically 5-10% of the consumed heat (Esping. B, 1996, Stridberg. S, 1985).

$$\dot{q}_{walls} = 2U_{wall} * A_{wall} * (T_{d,1} - T_{d,4}) \quad \text{(Eq. 26)}$$

$$\dot{q}_{floor} = U_{floor} * A_{floor} * (T_{d,1} - T_{d,4}) \quad \text{(Eq. 27)}$$

$$\dot{q}_{roof} = U_{roof} * A_{roof} * (T_{d,1} - T_{d,4}) \quad \text{(Eq. 28)}$$

$$\dot{q}_{trans} = \dot{q}_{walls} + \dot{q}_{floor} + \dot{q}_{roof} \quad \text{(Eq. 29)}$$

$$\dot{q}_{vent} = (h_4 - h_1) * m_{air} * L \quad \text{(Eq. 30)}$$

$$\dot{q}_{melt\ heat} = Cp_w\left(T_{d,1} - 0\right) + L_f \quad \text{(Eq. 31)}$$

$$\dot{q}_{woodheat} = \left((1 - u_i) * Cp_{wood} + u_i * Cp_w\right) * \left(T_{d,1} - T_{d,4}\right) \quad \text{(Eq. 32)}$$

$$Cp_{wood} = 115 + 0{,}005 * T_d \quad \text{(Eq. 33)}$$

$$\dot{q}_{leak} = \gamma * q_{heat} \quad \text{(Eq. 34)}$$

Results and Discussion

The performance of the calculation model was investigated by pine lumber with dimensions of 50x150 mm and a density of 430 kg/m^3 on dry basis. The initial moisture content of the lumber was set as 70 % and the end moisture content was set as 18%. Torksim simulated a standard Batch dryer, the ambient air temperature was set to 3 C and 70% humidity, according to average Swedish air conditions. Torksim produce a drying scheme of 70 h consists of dry and wet bulb temperature and lumber moisture content presented in Figure 4-5. The drying scheme was simulated with a maximum relative tension in the lumber of 30 % allowed.

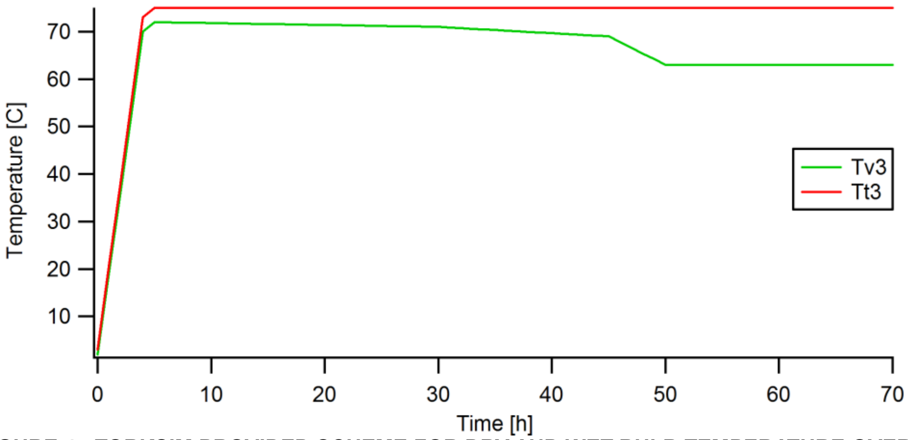

FIGURE 4 - TORKSIM PROVIDED SCHEME FOR DRY AND WET BULB TEMPERATURE OVER TIME

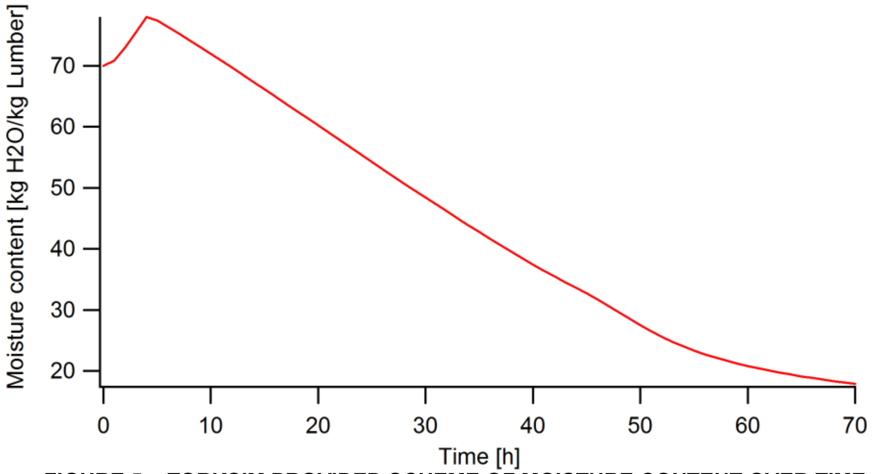

FIGURE 5 - TORKSIM PROVIDED SCHEME OF MOISTURE CONTENT OVER TIME

It should be noted that the lumber moisture content increased for the first hour, steam was supplied to the kilns to heat the lumber. The drying scheme was implemented as boundary conditions for the calculation model, as explained in chapter Methodology. The calculation procedure in the Program part I (idealic drying conditions) provide each specific air state of the drying cycle (point 1-4 in Figure 3). This was calculated in terms of wet and dry bulb temperature, absolute moisture content and energy content over time. Some of the results are shown in Figures 6-9 below.

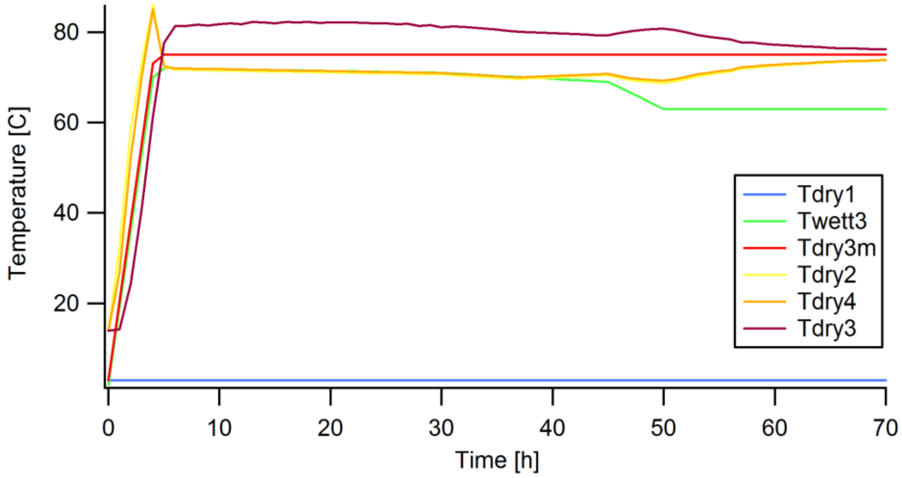

FIGURE 6 - DRY AND WET BULB TEMPERATURE IN THE DRYING CYCLE POINT 1-4

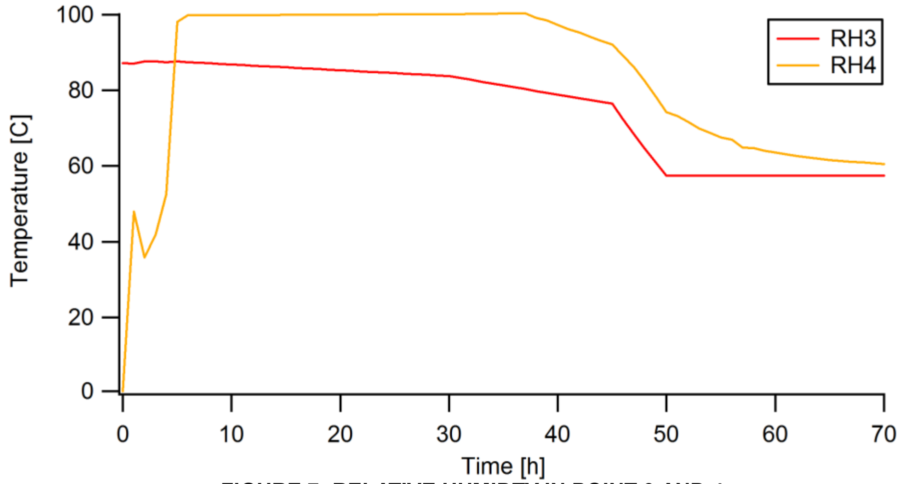

FIGURE 7- RELATIVE HUMIDTY IN POINT 3 AND 4

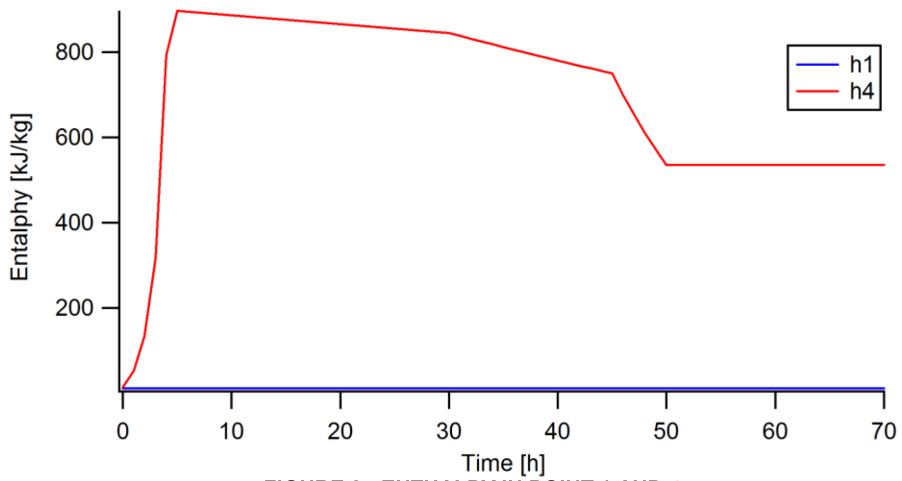

FIGURE 8 - ENTHALPY IN POINT 1 AND 4

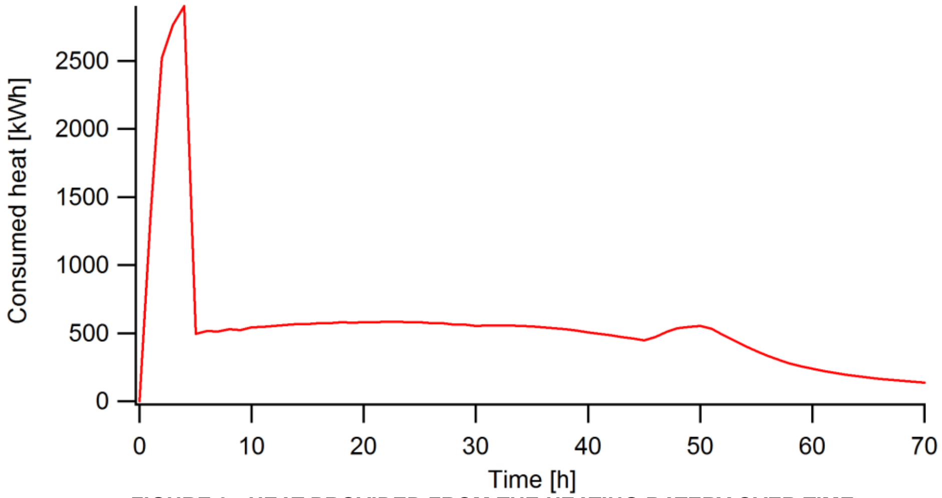

FIGURE 9 - HEAT PROVIDED FROM THE HEATING BATERY OVER TIME

The heat used during the drying process was calculated in the Program part II (Non-idealic drying conditions), numbered c in Figure 2. The heat consumption is divided into ventilation losses, leakage losses, transmission losses and wood heat losses. These heat losses contributions to the overall heat consumption are shown in Figure 10.

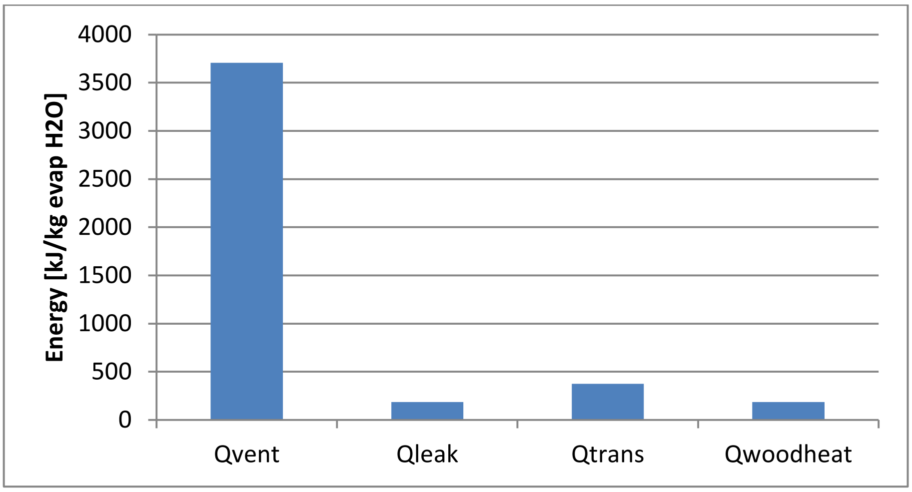

FIGURE 10 - USED ENERGY PER KG EVAPORATED WATER

The total heat consumption is calculated to be 4451 kJ/kgH2O (319 kWh/m^3). This is compared with experimental values made on similar drying conditions 4320 kJ/kgH2O (Esping B, 1996), 4500 kJ/kgH2O (Tronestad.S, 1993).

Conclusions

The general impression is that the calculation model gives an analytical model over the drying cycle. It provides appropriate data in terms of the drying temperatures and moisture content over the drying cycle. With changed initially boundary conditions the model can simulate each type of drying scheme and drying condition valid the lumber drying of batch kilns. Each type of energy losses can be observable. This gives a fast and more economical profitable analyse over the heat consumption that it would take to carry out an experiment for each specific drying conditions. The calculated heat consumption is close conformably to comparable made experiments in the literatures (Esping B, 1996), (Tronestad.S, 1993).

The known entries in the drying cycle give raise to use this model for analyses of other technologies which can be provided to increase the energy efficiency among the dryer.

Future work

This model was made to analyse the heat consumption during lumber drying in batch kilns. It is possible to modify so it will be valid for progressive kilns to. Additional technologies are likely to be implemented into the program to analyse further technologies aspect which can affect the energy efficiency. Technologies like heat exchanger, heat pumps, absorptions heat pumps, condense walls etc. A theoretically made reference sawmill will be implemented into the model, to get the system aspect into account in the model.

Acknowledgements

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Nomenclature

Mass	m	[kg/s]
Absolute moisture content	x	[kg H_2O/kg]
Pressure	P	[kPa]
Enthalpy	h	[kj/kgK]
Relative humidity	θ	[%]
Lumber moisture content	u	[kgH_2O/kg Lumber]
Density	ρ	[kg/m^3]
Temperature	T	[°C]
Adsadsa	r	[kJ/kg K]
Specific heat	C_p	[kJ/kg K]
Mixed amount of air	M	[kg entering air/kg circulation air]
Heat	Q	[kJ]
Specific heat	$\dot{q}$	[kWh/kg]
thermal conductivity	U	[W/m^2 K]
Area	A	[m^2]
Leack factor	ɣ	[%]
heat of fusion	L_f	[kJ/kg]

Subscript

1	Out door, point 1
2	Before the heating battery, point 2
3	middle of lumber package, point 3
3d	before lumber package, point 3b
4	after lumber package, point 4
t	time t=0
t-1	time t=-1
i	initially
w	water
d	dry
v	vapor
f	
tot	total
s,dry	saturated vapour pressure
wet	wet air
diff	difference
evap	evaporation of moisture
wood	wood
Air	air
Walls	kiln walls
Floor	kiln floor
Roof	kiln roof
Trans	Transmission
Melt heat	melt heat
Wood heat	wood heat
Wood	wood
Leak	leakage

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