Some Comparisons of Thermal Energy Consumption in a Temperate Versus a Subtropical Zone

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Abstract. Due to different ambient temperatures many would expect that the overall thermal energy consumption in a tannery in a hot climate zone is considerably lower than in a temperate zone. In reality it is somewhat more complex and worth comparing. The aim of this desk study is to compare consumption of thermal energy in temperate vs. (sub)tropical climate for two representative processes: float heating (bating and dyeing) and chamber drying, with the view of contributing towards overall assessment of thermal energy consumption for tanneries operating under rather different conditions. The energy consumption is calculated for 1 t of wet salted hides and assuming that 1000 kg of wet salted weight corresponds to 1100 kg of pelt weight containing 838 kg of water and 262 kg of collagen subsequently segregated into grain leather and usable splits. Float rates (200% on pelt/shaved weight), average inlet water temperatures (15 oC vs. 25 oC), process float temperatures for bating (35 oC) and dyeing (60 o C) have been defined. Similarly, for computation of thermal energy for chamber drying, identical initial (45 %) and target leather humidity (20 %) are set and average respective fresh air temperature (15 oC vs. 30 oC) and fresh air relative humidity (50% vs. 70%) estimated and operating conditions such as exhaust air temperature and relative humidity defined. Based on such parameters and assumptions, specific ratios for thermal energy consumption for float heating (bating & dyeing) and for chamber drying have been calculated and comparisons made; the results might not quite coincide with common perceptions. The energy needs computed are net amounts, i.e. regardless of the source and without taking into account any losses and disregarding energy consumption for ambient heating and/or cooling. Thus, the total energy needs are much higher. The ratios computed for grain leather are valid for split leather as well. However, if the solar energy is used to support water heating, the conditions in the tropic zone are substantially more favourable, due to higher insolation and higher efficiency factor (i.e. difference of the final vs. inlet water temperature). In any case, two very important factors, (i) temperature and (ii) humidity of inlet air are often overlooked in estimation of energy required for the crust and/or leather drying.

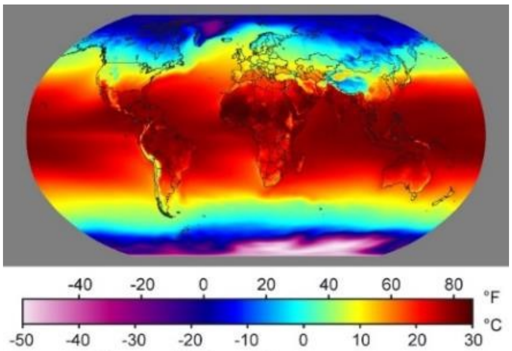


Fig. 1. World climate zones – annual mean temperatures (Source: http://www.wattsupwiththat.com)

The baseline data and/or assumptions:
The energy consumption is calculated for 1 t of wet salted hides and assuming that 1000 kg of wet salted weight corresponds to 1100 kg of pelt weight and 262 kg of grain leather and 88 kg of usable splits.

1 Float Heating

1.1 Temperate zone

1.1.1 Bating

Limed (pelt) weight: G = 1100 kg, the water being 838 kg, leather substance (collagen) 262 kg
Float 200% G = 2200 litres = 2200 kg
Inlet water temperature: tw = 15 o C

Process float temperature tf = 35 o C
Dry leather specific heat capacity: cl = 1.5 kJ/kg/oC
Water specific heat capacity: cw = 4.1814 kJ/kg/oC

The thermal energy necessary to heat the water for the bating float:
Q_{bating}, float = G * c * (tf – tw) = 2200 * 4.1814 * (35 – 15) = 2200 * 4.1814 * 20 = 184000 kJ
The thermal energy necessary to warm the pelt:
Q_{bating}, pelt = G * c * (tf – tw) = 262 * 1.5 * (35 – 15) = 262 * 1.5 * 20 = 7860 kJ
The thermal energy necessary to heat the water contained in the pelt:
Q_{bating}, water in pelt = G * c * (tf – tw) = 838 * 4.1814 * (35 – 15) = 838 * 4.1814* 20 = 70080 kJ
Q_{bating} total = 184000+7860+70080 = 261940 KJ = 262 MJ/t wet salted hides

1.1.2 Dyeing, fatliquoring

Shaved weight, grain: G = 262 kg containing about 130 kg of water, leather substance (collagen) 132 kg
Float 200%: G = 524 litres = 524 kg
Inlet water temperature: t_w = 15 ^{o}C
Process float temperature: t_f = 60 ^{o}C
Dry leather specific heat capacity: c_l = 1.5 kJ/kg/^{o}C
Water specific heat capacity: c_w = 4.1814 kJ/kg/^{o}C

The thermal energy necessary to heat the water for the dyeing and fatliquoring float:
$Q_{dyeing, float}$ = G * c * (t_f – t_w) = 524 * 4.1814 * (60 – 15) = 524 * 4.1814 * 45 = **98600 kJ**
The thermal energy necessary to heat the leather:
$Q_{dyeing, leather}$ = 132 * c * (t_f – t_w) = 132* 1.5 * (60 – 15) = 132 * 1.5 * 45 = **8910 kJ**
The thermal energy necessary to heat the water contained in the leather:
$Q_{dyeing, water in leather}$ = 130 * c * (t_f – t_w) = 130* 4.1814 * (60 – 15) = 130* 4.1814 * 45 = **24460 kJ**
$Q_{dyeing,}$ total = 98600 kJ + 8910 kJ + 24460 kJ = 132 MJ/ t wet salted hides

1.2 Subtropical zone

1.2.1 Bating

Limed (pelt) weight: G = 1100 kg, the water being 838 kg, collagen 262 kg
Float 200% G = 2200 litres = 2200 kg
Inlet water temperature: t_w = 25 ^{o}C
Process float temperature t_f = 35 ^{o}C
Dry leather specific heat capacity: c_l = 1.5 kJ/kg/^{o}C
Water specific heat capacity: c_w = 4.1814 kJ/kg/^{o}C

The thermal energy necessary to heat the water necessary for the bating float:
$Q_{bating, float}$ = G * c * (t_f – t_w) = 2200 * 4.1814 * (35 – 25) = 2200 * 4.1814 * 10 = **92000 kJ**
The thermal energy necessary to warm the pelt:
$Q_{bating, pelt}$ = G * c * (t_f – t_w) = 262 * 1.5 * (35 – 25) = 262 * 1.5 * 10 = **3930 kJ**
The thermal energy necessary to heat the water contained in the pelt:
$Q_{bating, water in leather}$ = G * c * (t_f – t_w) = 838 * 4.1814 * (35 – 25) = 838 * 4.1814* 10 = **35040 kJ**
$Q_{bating total}$ = 131 MJ/t wet salted hides

1.2.2 Dyeing, fatliquoring

Shaved weight, grain: G = 262 kg containing about 130 kg of water, leather substance (collagen) 132 kg
Float 200%: G = 524 litres = 524 kg

Inlet water temperature: t_w = 25 °C
Process temperature t_f = 60 °C
Dry leather specific heat capacity: c_l = 1.5 kJ/kg/°C
Water specific heat capacity: c_w = 4.1814 kJ/kg/°C

The thermal energy necessary to heat the water for the dyeing and fatliquoring float:
$Q_{dyeing, float}$ = G * c * (t_f – t_w) = 524 * 4.1814 (60 – 25) = 524 * 4.1814 * 35 = **76700 KJ**
The thermal energy necessary to heat the leather for dyeing and fatliquoring:
$Q_{dyeing, leather}$ = G * c * (t_f – t_w) = 132 * 1.5 * (60 – 25) = 132 * 1.5 * 35 = **6930 kJ**
The thermal energy necessary to heat the water contained in the leather for dyeing and fatliquoring:
$Q_{dyeing, water in leather}$ = G * c * (t_f – t_w) = 130 * 4.1814 * (60 – 25) = 130 * 4.1814* 35 = **19025 kJ**
$Q_{dyeing, total}$ = 102.6 MJ/t wet salted hides

2 Leather Drying

As said earlier, the energy consumption is calculated for the input of 1 t of wet salted hides giving 262 kg of grain leather and 88 kg of usable splits; it is also assumed that both in temperate and hot climate the leather humidity before drying is 45 % and after drying 20 %.
Thus, the base values for grain leather are:
Dry leather substance in 262 kg of wet leather:
262 * 0.55 = 144.1 kg of dry leather
Water content in the leather before drying: 262 – 144.1 = 117.9 kg
Dried leather weight with 20 % humidity: 144.1/0.8 = 180.1 kg
Water content in the dried leather: 180.1 – 144.1 = 36.0 kg
Water evaporated: 262 – 180.1 = **81.9 kg**

2.1. Temperate zone

The necessary data for the humid air are taken from the hx diagram and tables for humid air.
Fresh air temperature: t_f = 15 °C
Fresh air relative humidity: φ_f = 50 %
Fresh air absolute humidity: x_f = 0.005 kg H_2O/kg dry air
Fresh (humid) air enthalpy: h_f = 28 kJ/kg dry air
Volume of fresh air: v_f = 0.833 m^3/kg humid air
Exhaust air, temperature: t_e = 60 °C
Exhaust air, relative humidity: φ_e = 90 %
Exhaust air, absolute humidity: x_e = 0.135 kg H_2O/kg dry air
Exhaust (humid) air, enthalpy: h_e = 415 kJ/kg dry air
Volume of humid exhaust air: 1.16 m^3/kg humid air
The air capacity to absorb the evaporated water from wet leather:
x_e – x_f = 0.135 – 0.005 = 0.130 kg H_2O/kg dry air
Theoretic quantity of the air (expressed as dry air) needed to absorb the evaporated water:
81.9/0.130 = 630 kg of dry air
The volume of fresh air needed: 630 * 0.833 = **525 m³**
The specific thermal energy necessary for water evaporation from the wet leather and air heating:
$\Delta h = h_e - h_f$ = 415 – 28 = 387 kJ/kg dry air: 630 * 387 = 243810 kJ = **243.8 MJ**
Dry leather specific heat capacity: c_l = 1.5 kJ/kg/°C
Water specific heat capacity: c_w = 4.1814 kJ/kg/°C

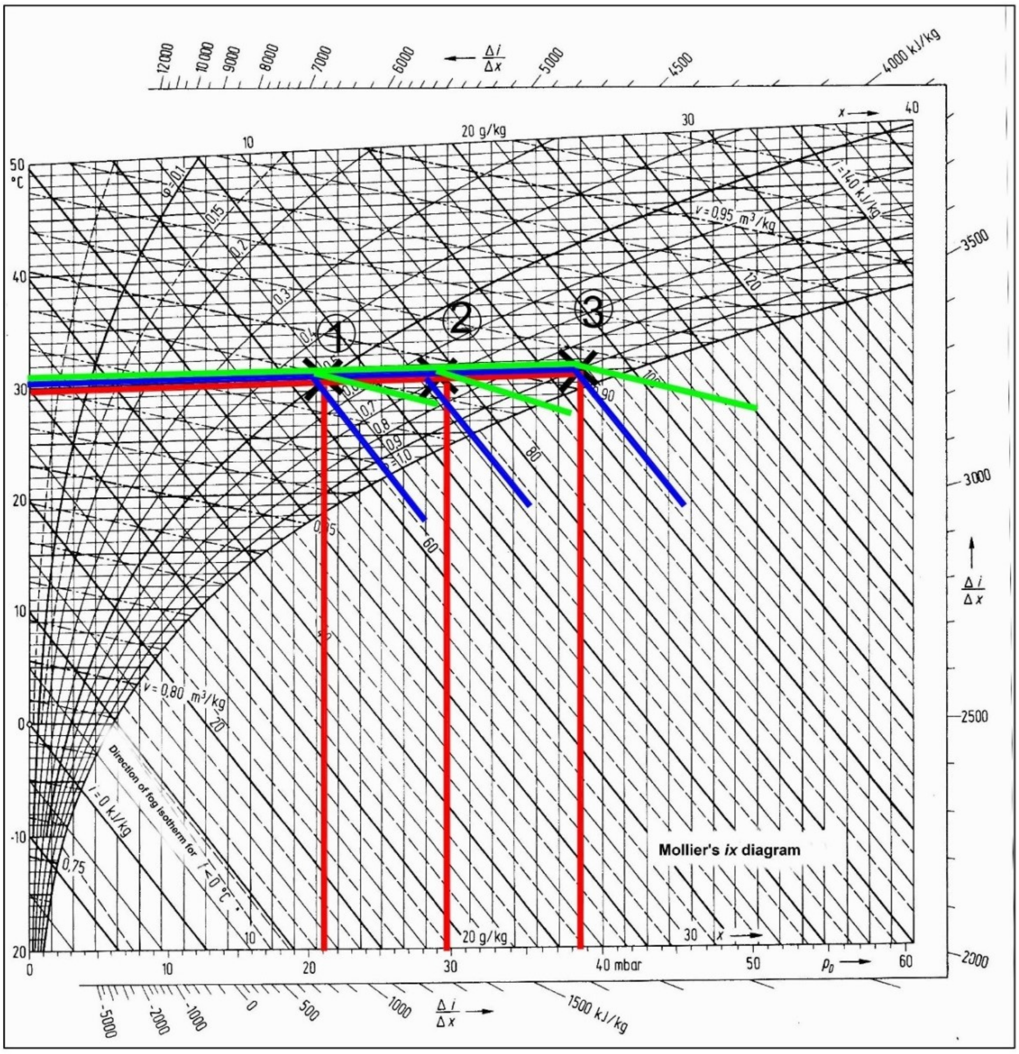
The heat (energy) necessary to heat the leather from the ambient temperature (15 °C) to outlet temperature (60 °C) :
fully dry leather: 144.1 * 1.5 * (60 – 15) = 144.1 * 1.5 * 45 = 9726.8 kJ = **9.73 MJ**
remaining humidity in dried leather: 36 * 4.1814 * 45 = 6774 kJ = **6.77 MJ**
The heat (energy) necessary for leather heating (15 - 60°C): 9.73 + 6.77 **= 16.5 MJ**
The net amount of thermal energy needed to dry leather: 243.8 + 16.5 = 260.3 MJ

2.2 Subtropical zone

2.2.1 Average air temperature 30 oC, relative humidity 70%

The necessary data for the humid air are taken from the hx diagram and tables for the humid air.
Fresh air temperature: t_f = 30 °C
Fresh air relative humidity: φ_f = 70 %
Fresh air absolute humidity: x_f = 0.019 kg H_2O/kg of dry air
Fresh (humid) air enthalpy: h_f = 76 kJ/kg of dry air
Volume of fresh air: v_f = 0.895 m^3/kg
Exhaust air, temperature: t_e = 60 °C
Exhaust air, relative humidity: φ_e = 90 %
Exhaust air, absolute humidity: x_e = 0.135 kg H_2O/kg of dry air
Exhaust air, enthalpy: h_e = 415 kJ/kg of dry air
Volume of exhaust air: 1.16 m^3/kg of air
The capacity to absorb evaporated water: $x_e - x_f$ = 0.135 – 0.019 = 0.116 kg H_2O/kg of dry air
The theoretical quantity of air (expressed as dry air) needed to absorb the evaporated water:
81.9/0.116 = 706 kg of dry air
The volume of fresh air needed: 706 * 0.895 = **632 m^3**
The specific thermal energy necessary for the evaporation of the water from the wet leather and air heating:
$\Delta h = h_e - h_f$ = 415 – 76 = 339 kJ/kg dry air; 706 * 339 = 239346 kJ = **239.3 MJ**
Dry leather specific heat capacity: c_l = 1.5 kJ/kg/°C
Water specific heat capacity: c_w = 4.1814 kJ/kg/°C
The heat (energy) necessary to heat the leather from the ambient temperature (30°C) to outlet temperature (60°C):
fully dry leather: 144.1 * 1.5 * (60 – 30) = 144.1 * 1.5 * 30 = 6484 kJ = **6.5 MJ**
the remaining humidity in dried leather: 36 * 4.1814 * 30 = 4516 kJ = **4.5 MJ**
The heat (energy) necessary for leather heating (30 - 60 °C): 6.5 + 4.5 **= 11.0 MJ**
The net amount of thermal energy needed to dry leather: 239.3 + 11.0 = 250.3 MJ

Water vapour with molecular mass of 18.04 g/mol is lighter than dry air (≈29 g/mol). Thus, the increase of water vapour content (humidity) results in lower air density because of Avogadro's law, which states "equal volumes of all gases, at the same temperature and pressure, have the same number of molecules." The higher number of water vapour molecules, the lower number of (heavier) air molecules.



1. Fresh Air 30°C, 50 % relative humidity

Fresh air, absolute humidity 0.0135 kg H_2O/kg of dry air
Enthalpy of fresh (humid) air 65 kJ/kg of dry air
Volume of fresh air 0.890 m^3/kg

2. Fresh Air 30°C, 70 % relative humidity

Fresh air, absolute humidity 0.019 kg H_2O/kg of dry air
Enthalpy of fresh (humid) air 76 kJ/kg of dry air
Volume of fresh air 0.895 m^3/kg

3. Fresh Air 30°C, 90 % relative humidity

Fresh air, absolute humidity 0.025 kg H_2O/kg of dry air
Enthalpy of fresh (humid) air 93 kJ/kg of dry air
Volume of fresh air 0.900 m^3/kg

Fig. 2. The main parameters of wet air (Mollier's diagram) – subtropical zone (Chart reading by M. Bosnić)

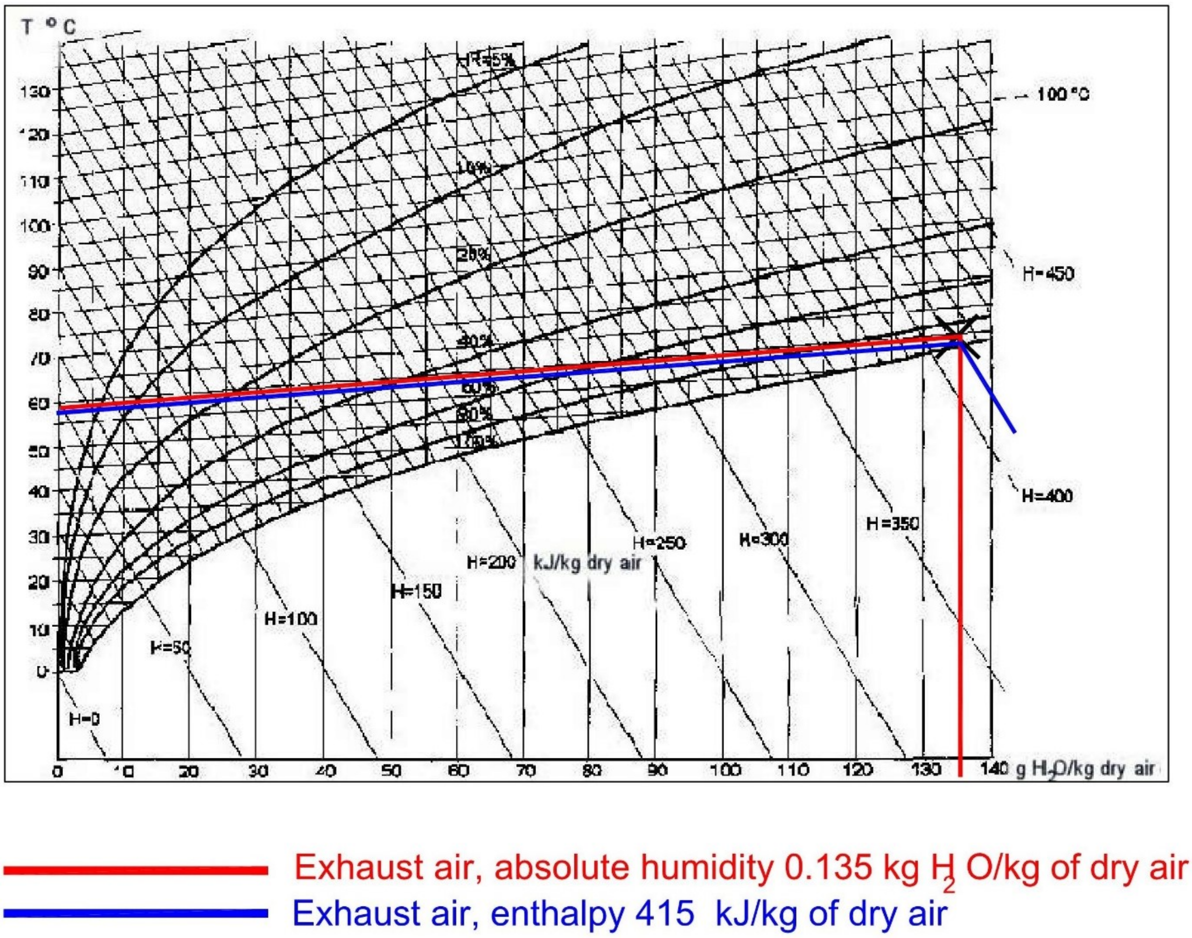


Fig. 3. The main parameters of wet (exhaust) air – 60 ^{0}C, relative humidity 90 % (Chart reading by M. Bosnić)

The following table contains a summary of data and the corresponding computations.

Table 1. Comparative overview of thermal energy needs for leather drying for different ambient temperatures and air humidity

Parameter	Ambient/inlet air temperatures and humidity			
	Temperate zone	Subtropical zone		
Fresh air temperature, t_f	15 ^{o}C	30 ^{o}C	30 ^{o}C	30 ^{o}C
Fresh air relative humidity, φ_f	50 %	50 %	70 %	90 %
Fresh air absolute humidity, x_f, kg H_2O/kg of dry air	0.005	0.0135	0.019	0.025
Fresh (humid) air enthalpy, h_f, kJ/kg of dry air	28	65	76	93
Volume of fresh air, v_f, m^3/kg	0.833	0.890	0.895	0.900
Exhaust air, temperature, t_e	60 ^{o}C	60 ^{o}C	60 ^{o}C	60 ^{o}C
Exhaust air, relative humidity, φ_e	90 %	90 %	90 %	90 %
Exhaust air, absolute humidity, x_e, kg H_2O/kg of dry air	0.135	0.135	0.135	0.135
Exhaust air, enthalpy, h_e, kJ/kg of dry air	415	415	415	415
Volume of exhaust air, m^3/kg of air	1.16	1.16	1.16	1.16
The capacity to absorb water, $x_e - x_f$, kg H_2O/kg of dry air	0.130	0.1215	0.116	0.110

Parameter	Ambient/inlet air temperatures and humidity			
	Temperate zone	Subtropical zone		
The theoretical quantity of air needed (expressed as dry air), kg of dry air	630 kg	674 kg	706 kg	745 kg
Thermal energy needed for water evaporation, $\Delta h = h_e - h_f$	243.8	236 MJ	239.3 MJ	240 MJ
The volume of fresh (humid) air needed	525 m³	600 m³	632 m³	671 m³
Dry leather specific heat capacity, kJ/kg/ºC	c_l = 1.5	c_l = 1.5	c_l = 1.5	c_l = 1.5
Water specific heat capacity, kJ/kg/ºC	c_w = 4.18	c_w = 4.18	c_w = 4.18	c_w = 4.18
The energy needed to heat the leather from the ambient to the outlet temperature of 60 ºC and humidity 20 %:				
- fully dry leather	9.73 MJ	6.5 MJ	6.5 MJ	6.5 MJ
- the remaining humidity in leather	6.77 MJ	4.5 MJ	4.5 MJ	4.5 MJ
The energy needed for leather heating	16.5 MJ	11.0 MJ	11.0 MJ	11.0 MJ
The total amount of thermal energy needed to dry leather	260.3 MJ	247.0 MJ	250.3 MJ	251.0 MJ

3 The comparison of net thermal energy needs

3.1 Float heating

3.1.1 Bating

$Q_{\text{bating total subtropical zone}}$ = 131 MJ/t of wet salted hides
$Q_{\text{bating total temperate zone}}$ = 262 MJ/t of wet salted hides
Ratio: 131/262 = 50 % or 1: 2

3.1.2. Dyeing, fatliquoring

$Q_{\text{dyeing total, subtropical zone}}$ = 103 MJ/t of wet salted hides
$Q_{\text{dyeing, fatliquoring total, temperate zone}}$ = 132 MJ/ of wet salted hides
Ratio: 103/132 = 0.78 = 78 % i.e. nearly 20 % less

Table 2. The comparison of net thermal energy needs for chamber drying

	Ambient/inlet air temperatures and humidity			
	Temperate zone	Subtropical zone		
	15 ºC, 50 %	30 ºC, 50 %	30 ºC, 70 %	30 ºC, 90 %
The total thermal energy needed to dry leather	260.3 MJ	247.0 MJ	250.3 MJ	251.0 MJ
The ratio subtropical vs. temperate climate	-	95 %	96.2 %	96.4%
The volume of fresh air needed, m³/t of w. s. hides	525 m³	600 m³	632 m³	670 m³
The ratio subtropical vs. temperate climate	-	114 %	120 %	128 %

The energy needs computed here are net amounts, i.e. regardless of the source and without taking into account any losses. Thus, the total energy needs are much higher. The ratios computed for grain leather are valid for split leather as well.

Fig. 4. A pole-drying tunnel (Source: Demaksan)

4 Conclusions

A simple computation based on estimated average yearly fresh water and air (ambient) temperatures shows that the amount of net thermal energy needed for heating the float in (sub)tropical zone (South India) is from 20% (dyeing) to about 50 % (bating) of that in the temperate zone (Middle Europe).

Chamber drying in (sub)tropical zone benefits from the higher ambient (air) temperature but at the same time it is negatively affected by high relative humidity and consequently much higher volume of fresh air required. However, the fact that the energy required for water evaporation[1] does not change much with water temperature ultimately prevails over parameters such as ambient (air) temperature and air humidity. Accordingly, energy consumption for chamber drying in (sub)tropical zone with average air temperature of 30^{o}C and relative humidity in the span of 50-90 % is only about 5 % less than in the temperate zone.

However, if the solar energy is used to support water heating, the conditions in the tropic zone are substantially more favourable, due to two factors:

- insolation
- efficiency factor (depends on the temperature difference of the *final vs. inlet water temperature*)

The insolation in the temperate zone (Europe) is approx. 1500 kWh/m^2/y (4.1 kWh/m^2/d), and in the tropical zone (South India) approx. 2200 kWh/m^2/y (6.0 kWh/m^2/d), so that the factor of proportionality is 1.5. Since the efficiency ratio case can be estimated as 1.05 it means that the solar based production of thermal energy in a hot climate country is about 1.6 times more favourable than in temperate climate.

[1] The **(latent) heat of vaporization** is the amount of energy (enthalpy) that must be added to a liquid substance to transform a quantity of that substance into a gas. The enthalpy of vaporization is a function of the pressure at which that transformation takes place.

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