HEAT PUMPS FOR WOOD DRYING – NEW DEVELOPMENTS AND PRELIMINARY RESULTS[*]

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ABSTRACT

This paper succinctly presents new developments, preliminary statements and a number of energy results in the area of high-temperature heat pump technology for wood drying in a Canadian economic environment. A hybrid (electricity/fossil), high-temperature technology has been investigated and then field tested over the last two years. Several technical developments were achieved at the level of fluid selection, refrigerant flow control and system stability, variable dehumidifying capacity and appropriate drying schedules. The present study demonstrates that the thermodynamic efficiency and specific energy performance of the developed high-temperature drying heat pumps have generally reached the initial designed targets. Refinements of the integrated control methods involving variable speed and electronic devices are currently being undertaken in order to avoid undesired operating conditions that could cause mechanical failures or inefficient dehumidifying processes. The current research program aims at diversifying the applicable thermodynamic cycles, testing new environmentally friendly refrigerants and advanced components, and developing more advanced drying control strategies.

Keywords: Wood Drying

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INTRODUCTION

The drying of resinous lumber, a process that is highly favorable to high temperatures, is essential to prevent the warping and cracking of the wood. In 2002, Canadian sawmills delivered 72 million m^3 such products, approximately 10% of which were produced in the province of Quebec (East of Canada) and where only 2% were dried by heat pumps and the rest through other technologies such as direct fire and the use of bark-, natural gas- or oil-burned boilers [Canada Statistics 2002]. In the 1970s and 1980s, the kiln drying industry promoted dehumidifier concepts, but the performance of such systems was often disappointing due to air flow and control problems, inadequate dehumidifying capacity and inappropriate kiln structures. The reliability of the systems was often low and equipment suppliers did not provide enough information on the actual performance of their systems. However, the best solution that would allow heat pumps to be effective as a means of drying wood would be to use them in combination with a traditional energy source at high temperatures to obtain similar drying speeds and energy savings. The technology of high-temperature heat pumps is not yet available, all the more so since early 90s environmental issues imposed the replacement of traditional CFCs used as high-temperature refrigerants. The merits of heat pump dryers however include lower energy consumed for each unit of water removed, accurate control of drying conditions, and enhanced product quality. Their limitations generally concern the need for regular maintenance, the risk of refrigerant leaks and higher initial capital costs compared to conventional dryers. Recently, more environment-friendly refrigerants have been developed and, two years ago, a North American heat pump manufacturer and a Canadian lumber producer decided to put their field experience and know-how to use in order to develop a high-temperature heat pump dryer application and to experiment their prototypes on an industrial scale, even if the processes involved in wood drying are highly non-linear and, consequently, the scale-up of dryers is generally difficult. Hydro-Quebec's Research Institute has actively contributed to the development of the first two industrial prototypes and to a field testing program aimed at providing customers with quantitative information on the reliability and efficiency of such systems.

DRYING SYSTEM CONFIGURATION

The sawmill facility chosen as the experimental site has been equipped since 1998 with two air forced, traditional 354 m^3-wood dryers made of insulated panels, each including 1,500-kW steam heating coils (Figure 1). An oil-burned boiler of 4,900-kW output capacity (82%) supplies both dryers with high-pressure saturated steam for heating and spraying. One of these dryers, where a maximum of 96 to 100 bundles enter on two train rails, has been converted into a hybrid dryer equipped with two high-temperature heat pumps and a back-up steam heating system.

Figure 1: View of the Experimental Wood Dryer (on left)

Charged at full capacity during the cold Canadian climate, the experimental dryer is theoretically able to generate drying temperatures of up to 116°C (240°F) in a lapse of 6 to 8 hours. However, heat losses and leakage technically lead to maximum dry temperatures of 82.2°C to 93.3°C (180°F to 200°F). A 56-kW low static pressure, longitudinal, six-blade fan with an outdoor motor, placed above a false ceiling ensured forced circulation of the air at 1.5 – 2.0 m/s (300 – 400 fpm) at the stacks of wood outlet. Mural deflectors and inversion of the rotation of the central fan at every 3 hours at the beginning and at every 2 hours at the end of the drying cycles contribute to obtaining uniform ventilation. Nine of the twelve existing air vents, placed in two rows on each side of the longitudinal fan, are kept closed in the hybrid dryer. To avoid air implosion risks, the three operational air vents open solely when the central fan changes its rotation direction and also when the actual dry temperature exceeds the set point. The high-temperature heat pumps, each equipped with a variable speed blower, are linked to the hybrid dryer (Figure 2). Compressors, evaporators and their electric/electronic controls are placed inside the adjacent mechanical room, while the condensers, as one design originality, are installed inside the kiln. Designed for industrial processes, the open-, belt-driven compressors are provided with oil pumps, external pressure relief valves and crankcase heaters. The used refrigerant, a non-toxic and non-flammable fluid, readily available in Canada and relatively inexpensive compared to conventional refrigerants, has a relatively high critical temperature compared to the highest process temperature and a normal boiling point les than the lowest temperature likely to occur in the system. Moreover, the saturation vapour pressure at highest design temperature is not so high as to impose design limitations on the system. Previous studies have shown that it has cooling capacities of up to 20% higher than the best older high-temperature refrigerants [Kasachki et al. 1994]. Multiple, parallel installed expansion valves are incorporated into the microprocessor-based temperature/process controllers that display the set point and the actual process temperatures.

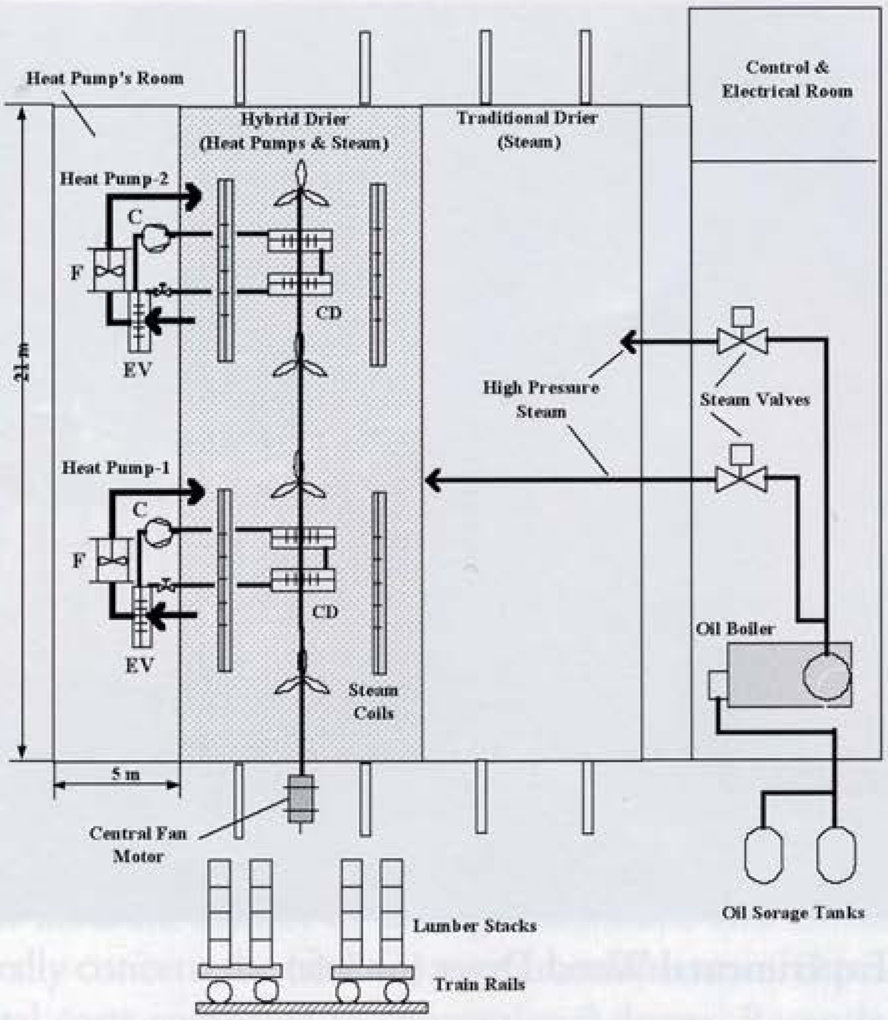

Figure 2 : General Layout of the Experimental Drying Plant
C – Compressor. EV – Evaporator. CD – Condenser. F – Fan

DRYING SCHEDULES

Humidity exists inside the wood boards as "free" (liquid or vapor) and "linked" (hygroscopic) water and it is practically admitted that the fiber saturation point is 30% of the dry basis moisture content. Displacement of the humidity through the wood is generally driven by affinity and capillarity (adhesion/cohesion) forces, vapor and moisture content gradients and diffusion, while the drying velocity is firstly governed by the ambient air capacity to absorb humidity and widely depends on the temperature and relative air and wood dryness. Three of several preliminary tests performed are presented here, respectively with white spruce *Picea glauca* (#70 and #88) and balsam fir *Abies balsamea* (#176) (see Table 2). All these batches were submitted to preheating periods at a maximum 87.7°C (190°F) dry temperature before each first step of the drying cycle, generally for a period of 6 to 8 hours in order to destroy the micro-organisms responsible for discoloring the sapwood. Presently, all preheating steps are performed at 93.3°C (200°F) dry temperatures. When the heat pumps started up (step 1), the moisture content first decreased linearly with time, a process followed by a non-linear decrease until the wood boards reached their equilibrium state and the drying cycle then shut down at the end of 5th or 6th step. The drying conditions of each step were established based upon moisture content, type of wood species, dimensions and quality of the wood, in conformity with an index established for Eastern Canada wood drying programs [Cech & Pfaff 2000]. For white spruce, which is normally easy to artificially dry, at initial moisture content of between 40 and 30%, the setting dry bulb temperature normally was 82.2 to 85°C (180 to 185°F) and the wet bulb temperature, 62.7°C (145°F). At a moisture content of less than 30%, the dry bulb temperature was generally 79.4°C (175°F) and the wet bulb temperature, 62.7°C (145°F). However, with balsam fir, which is harder to dry, when the initial moisture content was above 35%, the dry bulb temperature remained at 82.2°C (180°F) and the wet bulb at 79.4°C (175°F). Finally, for moisture contents lower than 25%, the setting dry bulb temperature attained 93.3°C (200°F) whereas the wet bulb temperature was 71.1°C (160°F). Changes in dry and wet temperatures settings during the tests were done on predetermined time-based schedules. For white spruce, steps 1 to 3 generally lasted 10 hours, while step 4 held out 20 hours, and step 5, 10 or even 20 hours depending upon the wood's actual moisture content. In the case of balsam fir, the first five drying steps each lasted 30 hours, while the 6th step lasted up to 15 hours. The main idea was to not exceed the average duration of traditional drying batches for the same species of dried wood. Finally, when the indoor dry bulb temperature was lower than the set point value, the steam valve opened gradually from 5% to100% upon a time-based schedule to fully recover the set point. However, some work should still be focused on improving the steam valves and air vent actual operation.

PRELIMINARY RESULTS

Thermodynamic Parameters

Heat pumps have normally not cycled at the start of preliminary drying processes, but they sometimes did that at the end as a result of the reduced ability of the wood to give up water at low moisture contents and the scheduled drop of the wet bulb temperature. The actual control strategy effectively allowed compressors to shut-down when the actual drier wet temperature has reached the set-point (Figure 3). After a given time delay, they were allowed to restart if the wet bulb temperature exceeded the presetting set point and only when a minimum presetting suction pressure was detected.

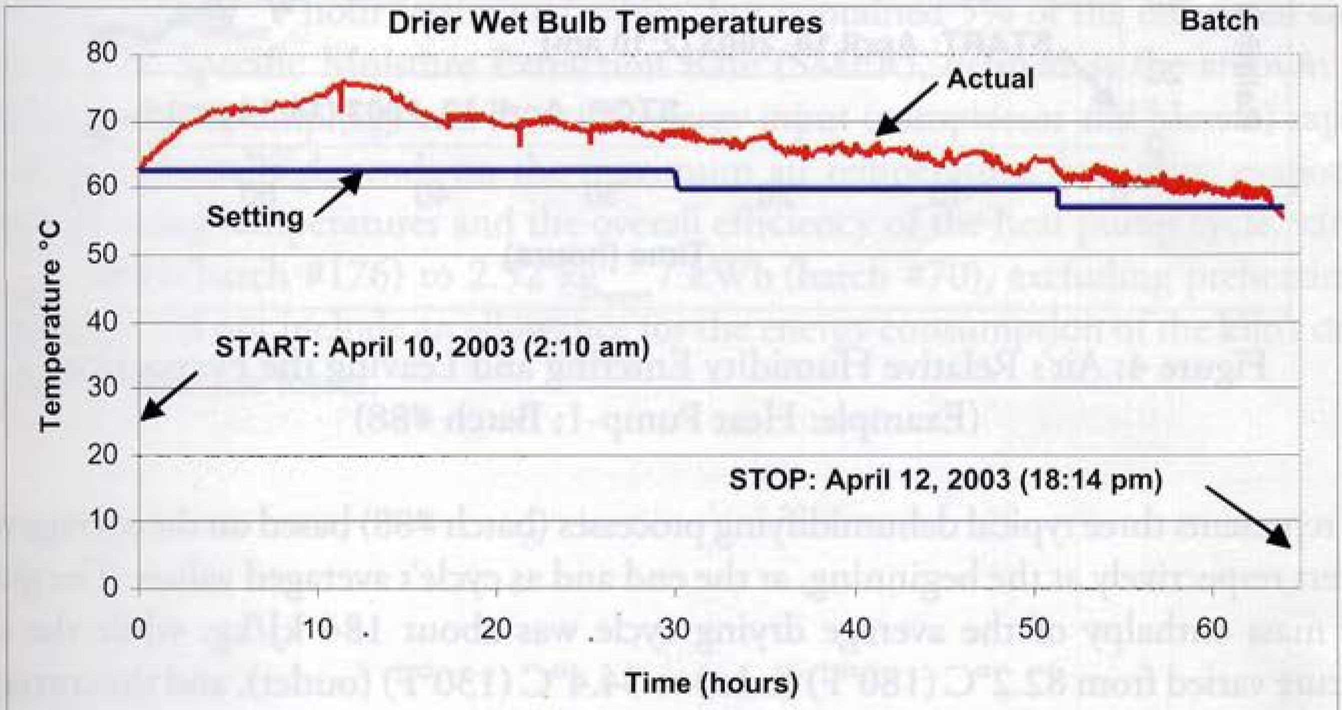

Figure 3: Profiles of Dryer Wet Bulb Setting and Actual Temperatures (Example: Batch #88)

The duration of drying batch #88, graphically presented here as a typical example, was 61.3 hours, and the respective graphs represent data when the compressor was in operation. They do not include the approximately 6-hour timber preheating step, which increased the dryer dry bulb temperature to 87.7°C (190°F). Within the reduced capacities conditions, the compressors ran with shaft electrical powers varying between 60 kW and 65 kW, and average compression ratios of 5 to 6. Stable suction and discharge pressure as well as an average condenser sub-cooling of 8°C (14.4°F) were ensured. Typical condensing temperatures varied around 100–105°C (212–220°F), about 20°C (36°F) higher than the kiln dry bulb temperature, and the evaporating temperature was in the range of 41.1 - 45.5°C (106 -114°F). The average relative humidity of the air entering the evaporators largely varied because of periodical changes in the rotation direction of the central fan, and has also continuously decreased in time. However, the relative humidity leaving the evaporators was almost constant at around 74% to 88%, except at the end of the cycle when it dropped to 70% (Figure 4). All measurements shown are original data scanned at 15-second intervals and saved at 2-minute intervals. The preheating step, which is necessary to prevent the discoloration of sapwood, allowed increase the kiln's absolute humidity up to 0.35 kg/kg before the dehumidifying process start-up (Figure 5). The maximum gradient of the absolute humidity across the heat pump's evaporators, varied from 0.214 kg/kg, immediately after starting the compressors, to about 0.039 kg/kg at the end of the showed drying cycle. The pick drying rate and efficiency of the heat pump were significantly higher than the average values, due to a higher wood moisture production rate at the beginning of the cycle. As in previous graphs, all variations of the shown parameters are due to the changes in the fan's direction of rotation that periodically modified the air flow pattern and humidity distribution inside the kiln.

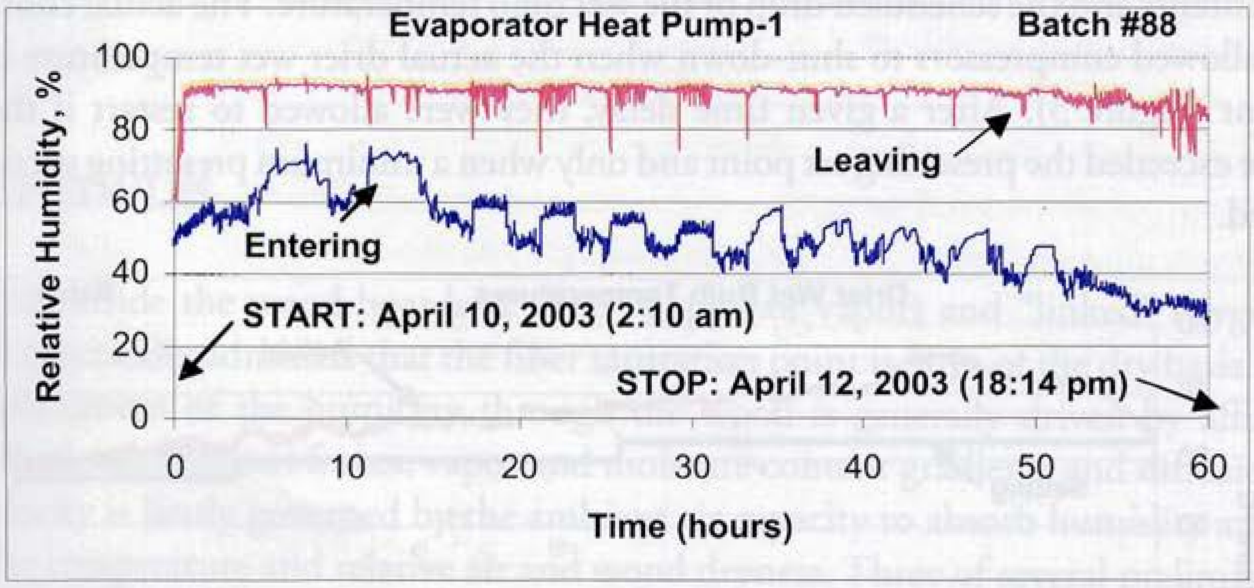

Figure 4: Air's Relative Humidity Entering and Leaving the Evaporator (Example: Heat Pump-1; Batch #88)

Figure 6 represents three typical dehumidifying processes (batch #88) based on the average measured parameters respectively at the beginning, at the end and as cycle's averaged values. The gradient of the air's mass enthalpy of the average drying cycle was about 184 kJ/kg, while the dry bulb temperature varied from 82.2°C (180°F) (inlet) to 54.4°C (130°F) (outlet), and the corresponding wet bulb temperature, from 65.8°C (140°F) to 48.8°C (120°F). Tests have yet to measure the actual oil consumption for preconditioning and back-up heating because the hybrid dryer was always in operation at the same time as the adjacent conventional dryer.

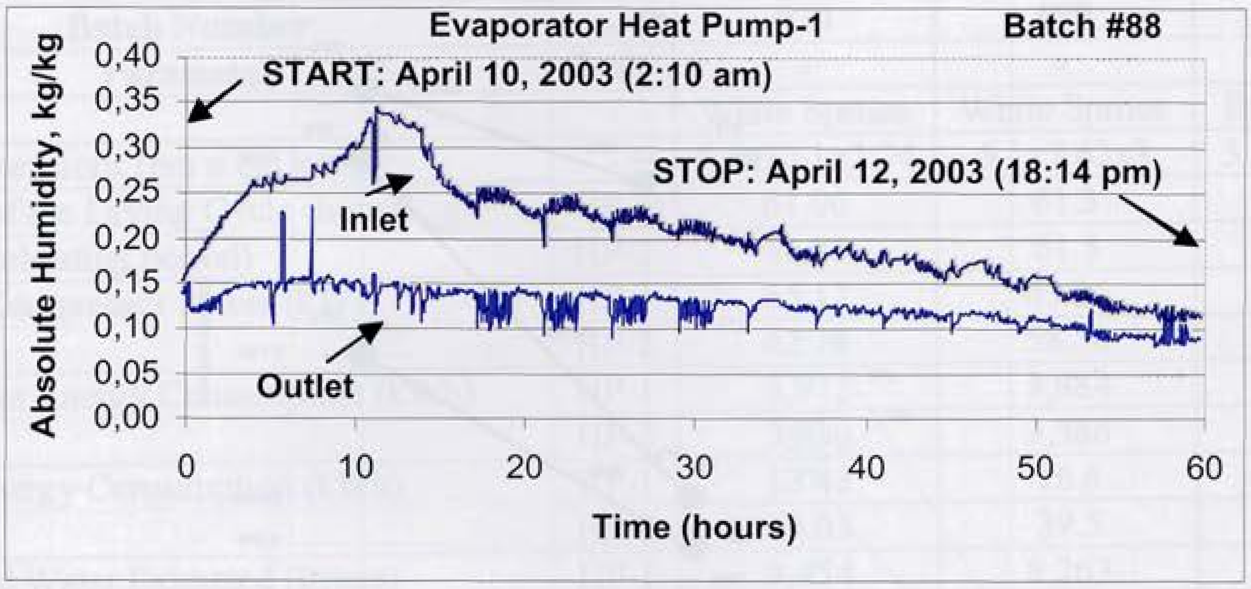

Figure 5: Air's Absolute Humidity Entering and Leaving the Evaporator (Example: Heat Pump -1; Batch #88)

Energy Performances

Table 1 provides the average energy performances of both high-temperature heat pumps for three typical dehumidification cycles. The moisture content of the timber prior to drying was typically in the range of 35 - 45% indicating that it had been air dried for a few days in the facility yard prior entering to kiln drying. The heat pump's average coefficient of performance (COP), defined as useful thermal power output (W) divided by electrical power input (W), varied from 3 to 4.6. The total average kiln rates of 313 kg_{water} / hour (batch #70), 263.2 kg_{water} / hour (batch #88) and 178.8 kg_{water} / hour (batch #176) do not include the venting losses that contributed on average approximately 90 kg_{water} / hour (estimated value), but contained 5% of the estimated condensed water losses. The Specific Moisture Extraction Rate (SMER), defined as the amount of water extracted by the heat pump (kg) and the total energy input (compressor and blower) expressed in kWh, and that generally depends on the maximum air temperature, humidity, evaporator and condenser operating temperatures and the overall efficiency of the heat pump cycle, varied from 1.46 kg_{water} / kWh(batch #176) to 2.52 kg_{water} / kWh (batch #70), excluding preheating energy consumption. It did not include an allowance for the energy consumption of the kiln's central fan or the venting moisture losses.

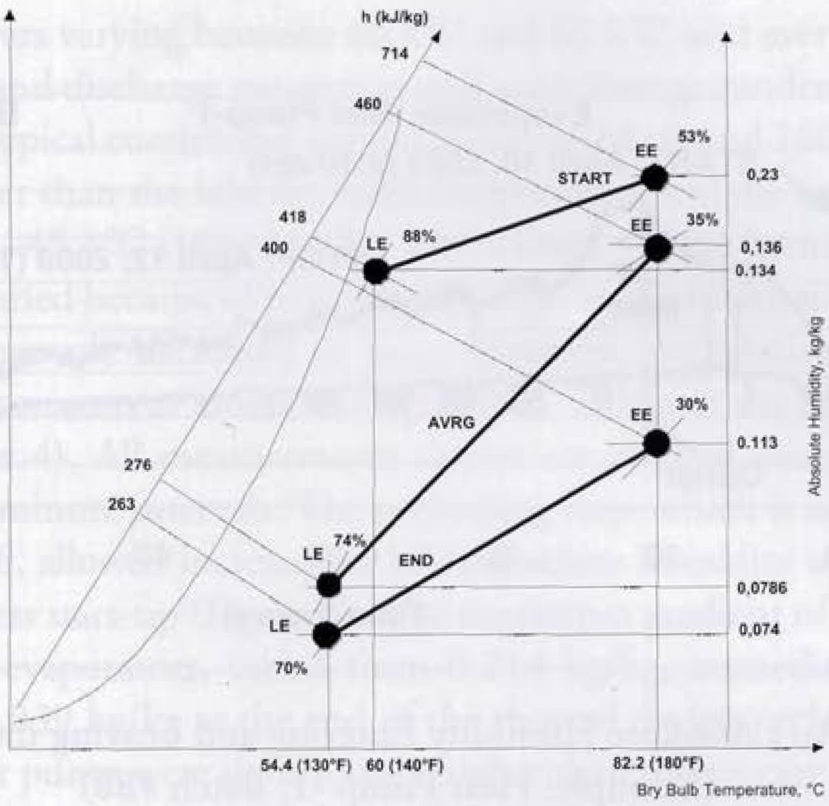

Figure 6: Air Dehumidifying Processes (Example: Heat Pump-1; Batch #88)
EE – Entering Evaporator; LE – Leaving Evaporator; START – at the beginning of the cycle;
AVRG – average drying cycle; END – at the end of the cycle

Another parameter, known as the Specific Energy Consumption (SEC), varied from 0.4 to 0.68 kWh / kg_{water}. The heat pump's consumption (compressor and blower) represented about 72% of the total electrical energy consumption, the balance being for the dryer's central fan (28%). As noted, at this time, any pertinent oil consumption measurement was done because the experimented hybrid kiln was always used in tandem with the neighboring conventional dryer, but instrumentation had already been installed on the oil supply line. The drying time to obtain white spruce with an approximate final moisture content of 17% to 19% averaged 2.5 days, while for balsam fir it averaged 6.3 days. Despite its longer duration, the drying of the balsam fir was less concerned with drying speed than that of the white spruce, the main operating focus values of which were to produce a high quality product. Last year, without heat pump dryers, the facility's specific cost for an annual production of about 39,600 m^3 of dried lumber was 14.75 US$/ *m*^{3} including all regular expenses (kiln operation, electrical and fossil energy consumption, equipment depreciation, insurance, etc.), of which energy only represented 6.86 US$/ *m*^{3}. The facility's objective is to reduce the energy-specific cost by at least 40%, and this also represents a goal of the current development steps related to high-temperature heat pumps.

Table 2: Energy Performances of Three Preliminary Drying Cycles

Batch Number	-	**#70**	**#88**	**#176**
Parameter	**Unit**	-	-	-
Timber	-	White Spruce	White Spruce	Balsam Fir
Board Dimensions (cm x cm x m)	-	5.1x10.1x2.74	5.1x7.62x3	5.1x7.62x3
Duration of the Drying Cycle (hours)	HP-1	61.00	61.3	151.4
(Except preheating period)	HP-2	61.00	61.3	151.4
Average Compressor Power (kW)	HP-1	65.12	63.36	61.0
	HP-2	62.78	58.50	57.14
Compressor Energy Consumption (kWh)	HP-1	3,972	3,884	9,235.4
	HP-2	3,830	3,586	8,651.0
Blower Energy Consumption (kWh)	HP-1	13.42	16.6	28.7
	HP-2	14.03	39.5	107.5
Condensed Water Extracted (Liters)	HP-1	9,454	8,263	13,550
	HP-2	9,655	8,478	13,531
Final Batch Average Moisture Content (%)	-	17.2	20.6	20.7
Average COP* (-)	HP-1	4.23	4.6	3.46
	HP-2	3.70	4.07	3.00
Average SMER** (kg_{water}/kWh)	HP-1	2.38	2.13	1.46
	HP-2	2.52	2.36	1.54
Average SEC*** (kWh/kg_{water})	HP-1	0.42	0.47	0.68
	HP-2	0.40	0.42	0.64

HP – Heat Pump; COP* – Coefficient of Performance; SMER** – Specific Moisture Extraction Rate (based on compressor and blower energy consumption); SEC*** – Specific Energy Consumption (based on compressor and blower energy consumption).

Operating Lessons Learned

Spread over several months, the first development step of high-temperature heat pump prototypes was aimed at ensuring a maximum operational stability of the thermodynamic parameters, establishing the reliability of the most sensible components (compressors, blowers, safety valves), checking the refrigerant/oil blend's behavior and optimizing the critical control sequences of the system. The experimental dehumidifier dryer operated in "extreme" temperature, humidity and corrosion conditions, and demonstrated specific feedback phenomena that do not occur in traditional air-forced/heated lumber dryers. Because some of the by-products that could be produced by chemical interactions between the lubricant and working fluid may be acidic and lead to accelerating the corrosion of the system components, periodical controls aimed to determine the chemical behavior of the mixture. After about 3,250 hours of operation, the refrigerant proved to be thermally stable and chemically inert at the highest temperatures occurring in the system and a first oil chemical analysis proved that there were no problems with the oil breaking down or failing. The oil still showed adequate viscosity and chemical stability as well as a good miscibility with the refrigerant. The initial designed capacity of the heat pumps proved to be too high and consequently, both compressors were slowed down by about 25% which finally resulted in a more adequate capacity, reduced head pressures and improved efficiency. Because the original employed expansion valves poorly controlled the refrigerant flowing, did not open fast enough and manufacturer leakage faults were detected, they were later replaced by new generation devices. A crack in the casting of an original pressure relief valve also indicated a manufacturer's defect, and finally both these components have been replaced to 20% higher pressure-limit valves. Other issues included the fact that the kiln was initially poorly insulated and leaky, and some system's components were prematurely corroding.

CONCLUSIONS

As a clean energy technology compared with traditional heat-and-vent dryers, high-temperature heat pump dehumidifiers offer interesting benefits for drying resinous timber. This paper presents the preliminary results of the development and field testing of two prototypes accentuating their thermodynamic parameters, preliminary energy performances and first operating lessons learned. The average measured specific moisture extraction rate of the heat pumps was 2.35 kg_{water} / kWh (white spruce) and 1.5 kg_{water} / kWh (balsam fir), while the average coefficients of performance generally varied from 3.0 to maximum of 4.6. The cycle's duration ranged from 2.5 days (white spruce) to 6.3 days (balsam fir) including the initial preheating steps. The refrigerant/oil mixture behaved well during more than 3250 hours of preliminary tests, proving good compatibility and chemical stability at condensing temperatures below 110°C (230°F). Better insulated and well maintained dryers are necessary to obtain drying temperatures higher than 100°C (212°F) as well as reducing the drying duration of resinous species by up to 25% and the total energy consumption by up to 50%. The current goals of the study include using more corrosive resistant components, variable speed central fan, further optimizing the drying schedules and general dryer operation and maintenance. Finally, it is expected to help local Canadian equipment suppliers to promote research and development of the technology and develop an appropriate market strategy. Specifications of high-temperature heat pump dehumidifier kiln energy use and a best-practice guideline must also be produced.

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