Techno-economic evaluation of microwave drying of wheat distiller’s grain with solubles in Saskatchewan

Maria Rosario P. Mosqueda and Lope G. Tabil

Department of Chemical and Biological Engineering, University of Saskatchewan, Saskatoon, SK S7N 5A9

Received: 2017 January 15, Accepted: 2017 November 29, Published: 2018 February 15

Mosqueda, M.R.P. and L.G. Tabil. 2017. Techno-economic evaluation of microwave drying of wheat distiller’s grain with solubles in Saskatchewan. Canadian Biosystems Engineering/Le génie des bio-systèmes au Canada 59: 8.23 - 8.37. The incorporation of microwave drying system in industry-scale drying of wet wheat distillers grain with solubles (WDGS) was evaluated for economic viability under three scenarios: (i) microwave drying, where only microwave energy was used in reducing WDGS from 70% to 10% moisture on wet basis (w.b.); (ii) booster drying, where microwave energy was applied after rotary drying when drying rates began to fall; and (iii) finish drying, where microwave drying was used near the end of the drying process. Complete replacement of the conventional hot air drying system with microwave energy was not economically feasible under the present set of assumptions. Although energy requirement during microwave drying was substantially lower than that of rotary drying, the cost of electricity in providing the microwave energy was seen as a major hindrance. Lower electricity rates, availability of cheaper power sources, and attractive market incentives, such as premium prices for high protein quality wheat DDGS, may be necessary to encourage ethanol producers to invest in the technology. Finish drying, which used the least amount of electrical energy among the three scenarios, was seen as the more economically viable option. Costs associated with the other DDGS production processes also have to be assessed to have a more comprehensive picture of the costs and the benefits of investing in microwave drying technology for protein quality improvement. Keywords: Wheat DDGS, microwave, booster drying, finish drying, ethanol co-product

INTRODUCTION

Wheat distillers dried grain with solubles (DDGS), a protein-rich co-product of fuel ethanol production, is primarily utilized in western Canada as an animal feed ingredient (FOBI Network 2011). Its efficient production and maximum utilization enhances the revenue generation potential of ethanol plants. A spreadsheet model maintained by Hofstrand (2013), for example, estimated that corn DDGS contributed between 7 – 26% of the total revenues generated from every gallon of ethanol. A similar revenue contribution may be assumed for wheat DDGS.

Reduced protein quality and a highly energy intensive drying process are two of the current challenges in the production and utilization of wheat DDGS (FOBI Network 2011). High incidence of heat-damaged proteins in wheat DDGS, primarily due to high temperature drying, hinders its marketing prospects, particularly if it is utilized as a substitute for the more expensive, high-protein ingredients in non-ruminant feed formulations (Widyaratne and Zijlstra 2007). It has also been estimated that the WDGS drying process could account about one-third of the total thermal demand in wheat ethanol plants (Murphy and Power 2008). Rising costs of natural gas and the potential for increased revenue generation from improved wheat DDGS quality could provide impetus for fuel ethanol producers to evaluate and improve existing plant processes.

In this study, microwave-based drying methods were investigated for their potential in minimizing both energy consumption and protein damage. Laboratory-scale investigations using a domestic microwave oven had demonstrated that with proper selection of drying conditions, microwave-based methods could provide DDGS the protein quality associated with low-temperature drying at much faster rates. Wheat wet distillers grain with...
solubles (WDGS) with 45% condensed distillers solubles (CDS) content and dried under 676 W microwave power (6.76 W/g of WDGS) or under a microwave convection nominal setting of 150°C-30% power (316 W, or 3.16 W/g of WDGS), for example, had comparable lysine and acid detergent insoluble crude protein (ADICP) contents with those attained under 80°C forced-air convection drying (Mosqueda et al. 2013). At these drying conditions and sample type (45% CDS), the drying rate constants (Page model parameter k) under microwave convection and microwave methods were 29% and 571% higher than the one obtained under 80°C forced-air convection, respectively. Microwave vacuum-dried wheat DDGS samples had lower ADICP content (10.87 – 14.41% d.b.) than that of an ethanol plant-dried (18.37% d.b.) sample (Mosqueda 2014). Both sample types were assumed to be derived from the same wheat WDGS batch as these were sourced on the same date from the same ethanol plant. Laboratory drying of ethanol plant-sourced wheat WDGS using the same equipment also showed that the drying rate constants of microwave methods (6.76-8.05 W/g of WDGS) were 208 – 433% higher than those achieved under 120°C forced-air convection (Mosqueda and Tabil 2011). These higher drying rates could translate to considerable energy savings.

The use of microwave energy, whether singly or in combination with forced-air convection or vacuum drying methods, had been investigated in drying a wide variety of plant-based materials. Some of these studies covered fruits (Mousa and Farid 2002; Meda et al. 2008; Sunjka et al. 2004; Dadali et al. 2007; Wang et al. 2009), grains and oilseeds (Lupinska et al. 2009; Walde et al. 2002), leafy plant parts (Cui et al. 2004; Ozkan et al. 2007), and bulbs, tubers, and root crops (Song et al. 2009; Lin et al., 1998; Sharma and Prasad, 2001). Areas commonly investigated include drying kinetics (Song et al. 2009; Drouzas et al. 1999), energy consumption and drying efficiency (Mousa and Farid 2002; Meda et al. 2008; Wang et al., 2009; Du et al., 2005), and retention of selected product quality characteristics (Cui et al. 2004; Sunjka et al. 2004; Lin et al. 1998; Alibas 2006; Ozkan et al. 2007; Lupinska et al. 2009). While these studies showed that the use of microwave energy could be an attractive method for drying plant materials, there is limited literature on the economic implications of its incorporation in the commercial processing of these materials. None was found on wheat WDGS drying.

The objective of this study, then, was to assess the economic viability of incorporating a microwave drying system for wheat DDGS production in Saskatchewan ethanol plants. Three scenarios were considered: (i) complete replacement of conventional hot air drying with a microwave drying system; (ii) use of microwave energy after the conventional hot air drying process reduced the moisture content of the sample to 50% w.b.; and (iii) use of microwave energy toward the end of conventional hot air drying when the moisture content of the sample is about 25% w.b. Combining both microwave and hot air systems could lower the drying cost compared to using microwave energy alone (Schiffman 2007).

**Materials and Methods**

A Microsoft Excel spreadsheet model was developed to evaluate the cost implications of incorporating a microwave drying system into Saskatchewan fuel ethanol plant operations. Evaluation was limited to the drying process only. Costs associated with plant design changes associated with microwave technology adoption as well as costs of operating the other DDGS production processes (centrifugation, evaporation, blending) were not considered.

**Plant capacity and annual operating time**

Saskatchewan has five grain-based ethanol plants, with nameplate capacities ranging from 15 to 150 million liters per year (MLPY) (Government of Saskatchewan 2013). Three of these plants utilized wheat as feedstock, while the other two utilized both wheat and corn. One of the wheat ethanol plants has integrated cattle feedlot operations that fully utilized its by-products (wet distillers grain and thin stillage) while the other two produced DDGS and sell this to third parties. These latter two plants, with nameplate capacities of 25 and 150 MLPY, were used as models in the assessment.

Annual operating time was assumed to be 8000 h, with about 4 weeks allowance for regular preventive maintenance programs and other unforeseen downtimes. This time is equivalent to operating about 92% of the plants’ nameplate capacities, if the plants were to operate all year with 24 h-days. This plant utilization percentage also fell within the performance range of the plants in 2010-2011, wherein ethanol production ranged from 72% to 98% of their nameplate capacities (Government of Saskatchewan 2013).

**Wheat DDGS production process**

Figure 1 presents the wheat DDGS production process considered in the techno-economic evaluation. Whole stillage, derived from ethanol production, is separated into two streams through centrifugation: (i) the solid fraction or the wet distillers grain (WDG), and (ii) the liquid fraction or the thin stillage. The thin stillage is subjected to evaporation to produce condensed distillers solubles (CDS), often referred to as “syrup” in industry parlance. Then, CDS is blended with WDG and dried to produce DDGS with 10% moisture (w.b.). In this evaluation, it is assumed that about 375 L of ethanol (95% purity) and 370 kg of DDGS (10% moisture w.b.) are produced for every tonne of wheat grain processed (FOBI Network 2011).

**Base case scenario** Reducing the wheat WDGS moisture from 70% (w.b.) to 10-12% moisture (w.b.) is usually accomplished using a rotary drum or a ring dryer. In this evaluation, the use of the direct-fired rotary dryers was considered as the conventional hot air drying method. Figure 2 shows a schematic diagram of blending and drying processes of DDGS production system involving a rotary drum dryer. It is further assumed that the air heater
Fig. 1. Unit operations involved in the production of wheat distillers dried grain with solubles in selected Saskatchewan fuel ethanol plants.

Fig. 2. A rotary drum drying system (With permission from GEA Barr-Rosin).
Microwave-based drying scenarios
The evaluation was made on three scenarios. Scenario 1 involved the use of microwave energy only in drying wheat WDGS from 70% to 10%, wet basis (w.b.). Scenarios 2 and 3 employed the sequential use of the conventional hot air and microwave drying systems.

In scenario 2, rotary drying initially reduced the moisture of the WDGS from 70% to 50% (w.b.). This was followed by microwave drying to further reduce the product moisture from 50% to 10% (w.b.). This scenario corresponds to what Schiffman (2007) referred to as booster drying. Microwave drying was employed when the drying rates under the conventional hot air system began to fall. In a previous investigation on laboratory-scale forced-air convection drying of ethanol plant-sourced wheat WDGS (Mosqueda and Tabil 2011), drying rates began to fall when moisture content was approximately between 55% (w.b.), under 120°C drying, and 62% (w.b.), under 40°C drying. Since typical drying temperatures employed in ethanol plants are higher than 120°C, it was assumed that drying rates would fall at moisture content lower than 55% (w.b.). A 50% moisture (w.b.) was assumed in the evaluation.

In scenario 3, rotary drying reduced the moisture of wheat WDGS from 70% to 25% (w.b.) and microwave drying was employed, thereafter, to further reduce the moisture of the partially dried material to 10% (w.b.). This scenario corresponds to what Schiffman (2007) referred to as finish drying. The 25% moisture was chosen for the evaluation because it was half the initial product moisture in the booster-drying scenario and near the target final product moisture of 10% (w.b.). These three drying scenarios were referred to in this report as “microwave” (scenario 1), “booster” (scenario 2), and “finish” (scenario 3).

Microwave drying system description
Figure 3 shows the schematic diagram of a commercially available microwave drying system used in the cost assessment. The system’s main components include: (i) microwave generator, which converts alternating current line power to microwave energy; (ii) the waveguide assembly, which delivers the microwave energy from the generator to the oven assembly; (iii) the oven or the applicator, which is a sealed enclosure where the material to be dried is horizontally carried on a microwave-inert conveyor belt and exposed to microwave energy; and (iv) a control system, which is used to monitor and regulate the entire drying operation (Cellencor, Inc. 2013).

It was assumed that the smallest and largest commercially available microwave drying systems were sized at 75 kW and 1 MW, respectively (Cellencor, Inc. 2013). The 75 kW microwave drying system, for example, comprised one - 75 kW 915 MHz microwave generator, one oven, a waveguide assembly, and a control panel while the 1 MW system would have ten - 100 kW 915 MHz microwave generators and five ovens. Each oven measures 3.66 m (length) x 1.32 m (width) x 1.22 m (height). Various size configurations between the smallest and largest units can be assembled using 75 kW or 100 kW microwave generators, depending on the microwave energy requirement of the process.

Drying system efficiency
Information on efficiency of microwave heating or drying systems from industry websites, brochures, journal articles, and reports showed a wide range of values. These are illustrated in Fig. 4. Schiffman (2007), for example, indicated a 45-50% conversion efficiency from electricity to microwave energy. This included about 4% loss in converting ac to dc, about 40% loss from converting dc to microwave, and waveguide and applicator losses of about 10%. Industry websites, on the other hand, indicated conversion efficiencies of 85-88% (Industrial Microwave Systems, LLC 2012; Envirowave Corporation 2013). Others used or indicated efficiency values between 70 to 75% (Doering 2011).
microwave drying was assumed at 100 °C. Process temperature under the booster and finish drying scenarios were assumed to be at 100 °C. The values of \( m \) and Hennessy 2008; Hasna 2011). Efficiency values found at the oven/applicator level ranged from 75% to 97% (Disman 1996; Schiffman 2007; Industrial Microwave Systems, LLC 2012; Cellencor, Inc. 2013).

Since drying system efficiency is a major factor in estimating energy requirement and costs (Disman 1996), the evaluation further used three energy efficiency levels under each of the three scenarios considered: low (50% microwave generator efficiency \( (e_G) \) and 75% applicator efficiency \( (e_A) \) or 38% overall system efficiency), medium (70% \( e_G \) and 85% \( e_A \) or 60% overall system efficiency) and high (85% \( e_G \) and 95% \( e_A \) or 81% overall system efficiency).

Mass and energy balance analyses

Mass flow rates The quantity of wheat WDGS entering the drying process, water to be evaporated, and the DDGS produced per hour were obtained using mass balance analyses, involving the following parameters: the plants’ nameplate capacities, % plant utilization, annual operating time, and initial and desired final product moisture contents under each drying scenario. Equations used and corresponding sample calculations are presented in the Appendix.

Total heat load The total heat load (\( E_T \)) for each drying scenario was estimated using Eq. 1, where \( m_w \) is the amount of water to be evaporated (kg) per hour, \( L_v \) is the latent heat of vaporization at 100 °C (2260 kJ/kg), \( m_p \) is the mass of the material to be dried per hour, \( c_p \) is the specific heat of the feed material, \( T_i \) and \( T_f \) represent the initial and final product temperature.

\[
E_T = m_w L_v + m_p c_p (T_i - T_f)
\]
(1)

The values of \( m_w \) and \( m_p \) were derived from mass balance analyses. Initial temperature of WDGS (70% moisture) was 80 °C, based from firsthand measurements made in the ethanol plant before the WDGS entered the drying process. Initial temperature of the other two feed materials for microwave drying under the booster and finish drying scenarios were assumed to be at 100 °C, since these already underwent hot air drying. Process temperature under microwave drying was assumed at 100 °C.

Specific heat \( (c_p \text{ kJ kg}^{-1}°C^{-1}) \) of the wheat WDGS (70% moisture) was obtained using a differential scanning calorimeter (DSC Q2000, TA Instruments, New Castle, DE). Samples were obtained from two production batches of a Saskatchewan ethanol plant and were evaluated using three replicates. A heating rate of 10 °C/min was used from an initial temperature of 20 °C to 240 °C. Experimental results at 80 °C were obtained and compared to Eq. 2, Choi and Okos’s generalized equation for specific heat (cited in Stroshine 1998), using the proximate composition obtained from a previous study (Mosqueda et al. 2014). The variable X in the equation represents the mass fraction of each chemical constituent. The subscripts \( w, p, f, c, \) and \( a \), represent water, protein, fat, carbohydrates, and ash, respectively. Test results of commercial samples were found to be 7 to 13% lower than the result from Eq. 2. Specific heat of the other feed materials (50% and 25% moisture DDGS) was estimated using Eq. 2.

\[
c_p = 4.180 X_w + 1.711 X_p + 1.928 X_f + 1.547 X_c + 0.908 X_a
\]
(2)

Estimation of equipment size and number

The results of mass and energy balance analyses were used in estimating the required size and number of the drying units under each scenario. Other assumptions are presented in the next pages with the corresponding sample calculations presented in the Appendix.

Microwave drying system The microwave energy requirement \( (E_G) \) for drying was determined using Eq. 3, where \( e_A \) is the efficiency of the applicator/oven and \( E_T \) is the total heat load, previously estimated in Eq. 2.

\[
E_G = \frac{E_T}{e_A}
\]
(3)

Using the results of Eq. 3, the equivalent number of 75 or 100 kW microwave generators, waveguide assemblies, and ovens/applicators required by each drying scenario was estimated. For simplicity in calculations, two microwave generators were assumed to be connected to each oven/applicator. A maximum of 1 MW was assumed to comprise one drying line.

Rotary dryer An evaporation rate of 14.64 kg·m⁻²·h⁻¹ (Gibson 1994) was used in estimating required size of
rotary direct-fired dryers. Equivalent dryer diameter, length, and number of units required under each drying scenario were estimated based on commercially available sizes (Zhengzhou Kehua Industrial Equipment Co., Ltd. 2013).

**Equipment and operating costs**

Cost estimation was limited to the drying equipment, fuel and utilities consumption, magnetron replacement, personnel and general maintenance. Except for personnel, the rest were among the basic cost components outlined by Disman (1966), Jolly (1976), and Schiffman (2007) in evaluating the economic viability of microwave drying systems. Depreciation and operating costs were summed to obtain the total unit cost of drying. Costs were calculated in Canadian dollars (CANS) per hour of operation but were expressed later on in CANS per tonne DDGS (10% moisture, wb) to facilitate comparison with historical market prices. Sample calculations for these cost items are presented in the Appendix.

**Microwave drying system** It was assumed that smallest microwave drying system (75 kW) costs about US$ 150,000.00 and the 1 MW system about US$ 1,200,000.00 (personal communication, K. Kaplan, President, Cellencor, Inc., 30 June 2013).

Equipment price was calculated based on the cost of each 1 MW system while fractions of 1 MW was estimated using the six-tenths rule (Chilton 1950), shown as Eq. 4. In this equation, I₁ represents investment cost for the desired capacity (Q₁), I₂ is the investment cost for the known capacity (Q₂) while x is the cost capacity factor, assumed at 0.60 (Chilton 1950). In this calculation, Q₁ and I₁ values were 1 MW and US$ 1,200,000.00, respectively.

\[
I_2 = I_1 \times \left(\frac{Q_2}{Q_1}\right)^x
\]  
(4)

In estimating the purchase price of a 5.6 MW system, for example, the 5 MW would be valued at US$ 1,200,000.00 per MW while the cost of the remaining fraction (0.6 MW) would be estimated using Eq. 4. Thus, the 5.6 MW system would be valued at US$ 6,883,226.00.

Installed cost of the drying equipment was assumed to be 1.4 times the purchase price (Couper et al. 2010). The 40% increase was assumed to cover for the cost of the allocated building space, instrumentation, ancillary equipment such as blowers to remove water vapor from ovens/applicators, specialized materials handling equipment, and other associated installation costs.

Since the equipment would be sourced from the US, other charges such as freight cost, US sales tax (4%), Canadian custom duties (8%), and goods and services tax (5%) were added to comprise the total equipment cost. Freight cost was estimated using number of required container vans to transport the equipment, distance between the supplier and the Saskatchewan plant, and the prevailing freight rate per mile (Freight Rate Index 2013). Foreign exchange rate of US$ 1.00:CANS 1.03 (Bank of Canada 2013a) was assumed.

Total equipment cost (Cₑ) was amortized over a 10-year economic life (Lₑ) using straight-line depreciation method. Depreciation cost per hour (CₑDep) was obtained using Eq. 5, where i is the interest rate, Sᵥ is the salvage value and tₐ is the annual operating time (8000 h). Interest rate used was 15% (Bank of Canada 2013b) while salvage value was assumed to be zero.

\[
C_{eDep} = \frac{(Cₑ - Sᵥ) \times (1+i)}{tₐ \times i}
\]  
(5)

**Rotary drying unit** The cost of the rotary direct-fired dryer (Cᵣd, in US$ 1000) was estimated using Eq. 6 (Couper et al. 2010), where A refers to the lateral surface area in sq. ft., while fₑ and fₑ are the drying gas and material factors, where values of 0.12 (direct contact) and 1.4 (stainless steel 304 type) were assumed, respectively.

\[
C_{rd} = 1.218 \left(1 + fₑ + fₑ \right) \exp(4.9504 - 0.5827 \ln(Aₚ)) + 0.0925 \left(\ln(Aₚ)\right)^2
\]  
(6)

The same previous assumptions for the installation cost, freight cost, US sales tax, Canadian customs duties, and goods and services tax in the microwave drying equipment were applied.

**Electricity** It was assumed that the ethanol plants did not generate their own electricity and relied on an external service provider for their power supply. Cost of electricity per hour (Cₑ) was estimated using Eq. 7, where Eₑ is the electrical energy consumption, in kW, and Uₑ is the unit energy cost, assumed at CANS 0.082 per kilowatt-hour. This unit cost was derived from calculations using the 2013 SaskPower standard rates (SaskPower 2013) covering basic monthly charge, demand charge, energy charge, and surcharges and taxes.

\[
C_{e} = E_{e} \times U_{e}
\]  
(7)

In microwave drying, Eₑ is equal to the amount of electrical energy drawn from the main supply lines (Eₛₑ), estimated using Eq. 8. In this equation, Eₛₑ was derived from Eq. 3 while εₑ represents the microwave generator efficiency.

\[
E_{s_{e}} = \frac{E_{g}}{\varepsilon_{e}}
\]  
(8)

In rotary drum drying, power requirement of electric motors used to drive dryer rotation was based on the accompanying technical details of each rotary dryer size chosen (Zhengzhou Kehua Industrial Equipment Co., Ltd. 2013). This power requirement was also verified using Eq. 9, proposed by the CE Raymond Division, Combustion Engineering (as cited in Krokiida et al. 2007) to determine power required to drive a dryer with flights. In this equation, bhp is the brake horsepower, Sₑ is rotational speed in rpm, D is the shell diameter (ft), w is the load of the material to be dried (lb), W is the total rotating load (equipment and material to be dried, lb), and D' is the riding-ring diameter and is equal to D + 2. Result of Eq. 9 was converted to kW and compared with the supplier-prescribed power requirement. The larger value of the two was used in the computation.

\[
bhp = \frac{S_{e}\left(4.75Dw + 0.1925D + 0.33W\right)}{100,000}
\]  
(9)
Water
About 23 – 38 L/min of water was needed to cool each microwave generator (Cellencor, Inc. n.d (a)). Cost of water consumption per hour ($C_W$) was estimated using Eq. 10, where $M_W$, $N_G$, and $U_W$ stand for the cooling water requirement per microwave generator (30 L/min), required number of microwave generators, and the cost of water, respectively. Cost of water was assumed at CAN$ 0.6201 per cubic meter, based on updated SaskWater non-potable water rates (personal communication, SaskWater customer service agent, 04 Oct 2013), plus a 7% tax rate.

\[
C_W = M_W *N_G * U_W * 1.07
\]  

(10)

Natural gas
The cost of natural gas per hour of operation ($C_{NG}$, Eq. 11) was obtained by multiplying the total energy requirement to be supplied by natural gas and the unit cost of natural gas ($U_{NG}$, CAN$/k^3$). Total energy requirement to be supplied by natural gas was estimated by dividing the result of Eq. 1 ($E_T$) with rotary dryer thermal efficiency ($\epsilon_T$) and combustion efficiency ($\epsilon_C$). The assumed values for $\epsilon_T$ were 0.50 and 0.75 (Krokida et al. 2007) while that for $\epsilon_C$ was 0.85 (Gilson Engineering Sales, Inc. n.d.), respectively. Unit cost of natural gas was derived from the average Jan – Aug 2013 price of US$ 3.70 per million BTU at the Henry Hub (Canadian Gas Association 2013). Since $E_T$ was expressed in kJ/s, a conversion factor of 3600 was introduced in Eq. 11 to express $C_{NG}$ on a per hour basis.

\[
C_{NG} = \frac{E_T * 3600}{9.87 * \epsilon_C} * U_{NG}
\]  

(11)

Magnetron replacement
It was recommended to replace the magnetrons annually or after 8000 h of operation (Industrial Microwave Systems, LLC 2012). Magnetron replacement cost per hour ($C_M$) was estimated using Eq. 12, where $N$, $U$, and $t_A$ stand for number of magnetrons, unit replacement cost, and the annual operating hours. The subscripts 75 and 100 refer to the magnetron size in kW. Unit costs of new 75 kW and 100 kW magnetrons were assumed at CAN$ 8485.00 and CAN$ 9806.00, respectively, inclusive of US sales tax (4%), custom duties (8%), goods and services tax (5%), and freight cost. Magnetron price quotes were obtained from a US supplier.

\[
C_M = \frac{N_{75}* U_{75} + N_{100} * U_{100}}{t_A}
\]  

(12)

General maintenance cost
General maintenance cost per hour ($C_{GM}$, Eq. 13) of the microwave and rotary drying system was assumed at 2% (Schiffman 2007) and 10% (Krokida et al. 2007) of the total installation cost, respectively. In Eq. 13, $C_i$ is the total installation cost, $p_i$ is the percentage of the total installation cost, and $t_A$ is the annual operating hours of the plant.

\[
C_{GM} = \frac{p_i * C_i}{t_A}
\]  

(13)

Personnel
Average annual salary of plant personnel was assumed at SaskWater engineers and geoscientists for 2013 (APEGS 2013). Number of personnel ($N_M$) for the 25 and 150 MLPY plants was assumed to be 10 and 40, respectively. Labor cost directly associated with the drying process was determined by dividing the total labor cost with the total number of major ethanol and DDGS unit operations. Ten unit operations were used in the calculation.

Incorporating microwave drying technology into existing plant operations requires the workforce to have a new set of specific skills and knowledge and to be more adaptable with the associated changes in plant operations. To meet this need, it was assumed that an appropriate training program would be crafted and implemented to benefit existing plant personnel in various aspects of production, equipment maintenance, materials handling, laboratory, and management of DDGS processes. Training cost ($C_T$) was pegged at CAN$ 1,800.00 per person per year ($U_M$) and estimated using Eq. 14.

\[
C_T = \frac{U_M * N_M}{t_A}
\]  

(14)

RESULTS AND DISCUSSION
Tables 1 and 2 summarize the evaluation results for the 25 and 150 MLPY ethanol plants, respectively while Fig. 5 shows the breakdown of the energy requirements for the microwave, boost, finish, and rotary drum drying systems at high efficiency levels.

Energy requirement
Rows b and d of Tables 1 and 2 show the energy input requirement per unit time at the dryer and at the main power supply line. To dry the same amount of wheat WDGS to the same target moisture level, these tables and Fig. 5 showed that microwave drying (scenario 1) required the least amount of energy per unit time among the scenarios. The energy requirement for microwave drying was 49-60% and 23-40% lower than rotary drying when the latter was assumed to operate at 50% and 75% thermal efficiency, respectively.

This was followed by booster drying (scenario 2), with an energy requirement that is 10-14% and 0-6% lower than rotary drying at the same thermal efficiency.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure.png}
\caption{Energy consumption of drying wheat distillers grain with solubles under microwave, boost, finish, and rotary drum drying methods. Assumed thermal efficiencies of rotary drum and microwave drying were at 75% and 81%, respectively.}
\end{figure}
Table 1. Techno-economic evaluation results of drying wheat distillers grain with solubles using rotary, microwave, booster, and finish drying systems in a 25 MLPY\textsuperscript{1} Saskatchewan ethanol plant operating at 92\% of their nameplate capacity. Drying systems were evaluated at two (low, high) efficiency levels\textsuperscript{2}.

<table>
<thead>
<tr>
<th>Particulars</th>
<th>Rotary drying</th>
<th>Scenario 1 - Rotory Low</th>
<th>Scenario 1 - Rotory High</th>
<th>Scenario 2 - Booster Low</th>
<th>Scenario 2 - Booster High</th>
<th>Scenario 3 - Finish Low</th>
<th>Scenario 3 - Finish High</th>
</tr>
</thead>
<tbody>
<tr>
<td>a. Material capacity (moisture, wb)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WDGS input rate, kg h\textsuperscript{-1} (70%)</td>
<td>8510.0</td>
<td>8510.0</td>
<td>8510.0</td>
<td>8510.0</td>
<td>8510.0</td>
<td>8510.0</td>
<td>8510.0</td>
</tr>
<tr>
<td>DDGS output rate, kg h\textsuperscript{-1} (10%)</td>
<td>2836.7</td>
<td>2836.7</td>
<td>2836.7</td>
<td>2836.7</td>
<td>2836.7</td>
<td>2836.7</td>
<td>2836.7</td>
</tr>
<tr>
<td>b. Energy input during drying, kJ s\textsuperscript{-1}</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rotary dryer efficiency:</td>
<td>9703.1</td>
<td>4951.1</td>
<td>3908.8</td>
<td>8753.4</td>
<td>8353.5</td>
<td>9465.7</td>
<td>9365.7</td>
</tr>
<tr>
<td>c. Equipment size and number</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rotary drying system</td>
<td>2.4 x 20</td>
<td>1.8 x 14</td>
<td>1.8 x 14</td>
<td>2.2 x 18</td>
<td>2.2 x 18</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MW drying system</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total size, kW</td>
<td>5000</td>
<td>3950</td>
<td>1900</td>
<td>1500</td>
<td>500</td>
<td>400</td>
<td></td>
</tr>
<tr>
<td>No. of ovens</td>
<td>25</td>
<td>20</td>
<td>10</td>
<td>8</td>
<td>3</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>d. Energy requirement from source, kW</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rotary dryer efficiency:</td>
<td>11584.2</td>
<td>10000.0</td>
<td>4647.1</td>
<td>11975.9</td>
<td>9940.6</td>
<td>11746.2</td>
<td>11216.8</td>
</tr>
<tr>
<td>e. Drying cost, CAN$/t\textsuperscript{-1} DDGS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rotary dryer efficiency:</td>
<td>101.16</td>
<td>394.80</td>
<td>394.80</td>
<td>394.80</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\textsuperscript{1}MLPY – million liters of ethanol per year;
\textsuperscript{2}Microwave drying system efficiency: low (50\% generator efficiency, 75\% applicator efficiency), and high (85\% generator efficiency, 95\% applicator efficiency); Rotary drying efficiency: low (50\% dryer efficiency, 85\% combustion efficiency) and high (75\% dryer efficiency and 85\% combustion efficiency).

Table 2. Techno-economic evaluation results of drying wheat distillers grain with solubles using rotary, microwave, booster, and finish drying systems in a 150 MLPY\textsuperscript{1} Saskatchewan ethanol plant operating at 92\% of their nameplate capacity. Drying systems were evaluated at two (low, high) efficiency levels\textsuperscript{2}.

<table>
<thead>
<tr>
<th>Particulars</th>
<th>Rotary drying</th>
<th>Scenario 1 - Rotory Low</th>
<th>Scenario 1 - Rotory High</th>
<th>Scenario 2 - Booster Low</th>
<th>Scenario 2 - Booster High</th>
<th>Scenario 3 - Finish Low</th>
<th>Scenario 3 - Finish High</th>
</tr>
</thead>
<tbody>
<tr>
<td>a. Material capacity (moisture, wb)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WDGS input rate, kg h\textsuperscript{-1} (70%)</td>
<td>51060.0</td>
<td>51060.0</td>
<td>51060.0</td>
<td>51060.0</td>
<td>51060.0</td>
<td>51060.0</td>
<td>51060.0</td>
</tr>
<tr>
<td>DDGS output rate, kg h\textsuperscript{-1} (10%)</td>
<td>17020.0</td>
<td>17020.0</td>
<td>17020.0</td>
<td>17020.0</td>
<td>17020.0</td>
<td>17020.0</td>
<td>17020.0</td>
</tr>
<tr>
<td>b. Energy input during drying, kJ s\textsuperscript{-1}</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rotary dryer efficiency:</td>
<td>58218.8</td>
<td>29706.8</td>
<td>23452.8</td>
<td>52520.9</td>
<td>50120.9</td>
<td>56794.2</td>
<td>56194.3</td>
</tr>
<tr>
<td>c. Equipment size and number</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rotary drying system</td>
<td>2.8 x 24</td>
<td>2.8 x 24</td>
<td>2.8 x 24</td>
<td>2.8 x 24</td>
<td>2.8 x 24</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MW drying system</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total size, kW</td>
<td>29750</td>
<td>23500</td>
<td>11400</td>
<td>9000</td>
<td>2850</td>
<td>2250</td>
<td></td>
</tr>
<tr>
<td>No. of ovens</td>
<td>149</td>
<td>118</td>
<td>58</td>
<td>45</td>
<td>15</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>d. Energy requirement from source, kW</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rotary dryer efficiency:</td>
<td>69617.0</td>
<td>59500.0</td>
<td>27647.1</td>
<td>71836.4</td>
<td>59624.7</td>
<td>70102.1</td>
<td>67049.1</td>
</tr>
<tr>
<td>e. Drying cost, CAN$/t\textsuperscript{-1} DDGS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rotary dryer efficiency:</td>
<td>95.43</td>
<td>390.14</td>
<td>215.75</td>
<td>212.45</td>
<td>145.00</td>
<td>122.69</td>
<td>106.21</td>
</tr>
</tbody>
</table>

\textsuperscript{1}MLPY – million liters of ethanol per year;
\textsuperscript{2}Microwave drying system efficiency: low (50\% generator efficiency, 75\% applicator efficiency), and high (85\% generator efficiency, 95\% applicator efficiency); Rotary drying efficiency: low (50\% dryer efficiency, 85\% combustion efficiency) and high (75\% dryer efficiency and 85\% combustion efficiency).
levels. Microwave drying under this scenario accounted 18-29% of the total energy requirement and removed about 40% of the water targeted for evaporation. The energy requirement of finish drying (scenario 3) was closest to that of rotary drying. The microwave-drying phase under this scenario removed 10% of the total moisture to be evaporated and accounted 4-7% of the total energy requirement. Values for energy requirement at the source (row d of Tables 1 and 2) per unit time took into account the combustion efficiency of natural gas in the case of rotary drying and microwave generator efficiency in microwave drying.

Lower energy requirement of microwave drying (row b of Tables 7.1 and Table 7.2) was due to the use of higher efficiency levels compared to rotary drying. Energy efficiency at the microwave applicator/oven was assumed to range from 75% to 95% while efficiency at the rotary dryer was at 50-75%. Unlike in rotary drying, microwave energy directly couples with the material to be heated and is not used to heat the air surrounding the material and the dryer walls and other parts of the system (Schiffman 2001; 2007). The internal heat generated by the microwave field results to an internal pressure gradient within the material that enables higher drying rates compared to that observed in conventional hot air drying (Schiffman 2001; 2007).

Energy requirement for microwave drying would be derived from electricity. About 98% of the energy requirement for rotary drum drying would be sourced from natural gas, which would cost about CANS 0.013 per kWh, and the remaining 2% would be from electricity to run the motors needed for drum dryer rotation.

In booster drying, about 26% of the total energy requirement would be supplied by electricity while the bulk (74%) would be sourced from natural gas. In finish drying, electricity and natural gas accounted about 8% and 92% of the total energy requirement, respectively. Since the cost of natural gas would be about 5-6x lower than the cost of electricity, on a per kilowatt-hour basis, rotary drum drying would be cheapest method and microwave drying the most expensive. Because of the lower amount of electricity required in finish drying, this drying method would have a cost closest to rotary drum drying.

**Equipment size, number, and cost**

Tables 1 and 2 (row c) also show the estimated equipment size and number required under the various drying scenarios.

Under rotary drying, the 25 MLPY and the 150 MLPY plants required three units of 2.4 m x 20 m and 12 units of 2.8 m x 24 m rotary drum dryers, respectively.
These correspond to the estimated initial equipment costs of about CANS 4.45 million and CANS 14.88 million, respectively. Use of 100% microwave energy (scenario 1), on the other hand, required initial equipment costs that were about 1.7 to 2.5 times higher than that of rotary drying. Microwave drying equipment under scenario 1 was estimated to cost about CANS 4.91 – 6.18 million and CANS 29.24 – 36.8 million for the 25 and 150 MLPY plants, respectively.

Equipment size and number required under booster and finish drying scenarios are also reflected in Tables 1 and 2. Equivalent initial equipment costs for the 25 MLPY plant, in CANS, were 3.82 - 4.17 million and 3.15 - 3.25 million under the booster and finish drying scenarios, respectively. For the 150 MLPY plant, estimated equipment costs were CANS 19.80 - 22.99 million for booster drying and CANS 15.41 – 15.99 million for finish drying.

Efficiency levels assumed for the microwave drying system substantially affected the size and number of drying equipment and consequently, the associated acquisition and operating costs. Drying using the least efficient microwave system (50% microwave generator efficiency and 75% applicator efficiency) under scenario 2 in the 25 MLPY plant, for example, would require five more microwave ovens than the most efficient system assumed (85% generator efficiency, 95% applicator efficiency). In the 150 MLPY, this translates to needing 31, 13, and three ovens more under microwave, booster, and finish drying, respectively.

Row e of Tables 1 and 2 show the estimated unit costs of drying under each scenario for the 25 and 150 MLPY plants, respectively. Depending on the plant size and drying system efficiency level, drying costs in CANS per tonne of DDGS were 77.99 - 101.16, 90.10 - 134.13, 132.68 – 219.31, and 215.75 – 394.80 under rotary, finish, booster, and microwave drying scenarios, respectively.

Figure 6 presents the contribution of each cost component to the total drying cost under each scenario. Although all scenarios required substantial equipment investment, the equivalent depreciation costs only accounted about 13-27% of the drying costs. In rotary drying, depreciation is about 21-27% of the total cost, 13-18% in microwave drying, 14-22% in booster drying, and 15-25% in finish drying.

The bulk of the estimated drying costs came from electricity and natural gas consumption. Cost of electricity per kWh was about 5 times higher than that of natural gas, thus, its increased use during drying would lead to higher total drying cost. In microwave drying, electricity costs ranged from CANS 134.33 to 289.07 per tonne of DDGS and comprised about 61% to 73% of the total drying cost. Lowering electricity cost, through lower power rates, use of cheaper alternative energy sources and availability of even more efficient microwave drying systems, could substantially improve the cost of producing microwave-dried DDGS. In contrast, the costs of natural gas consumption during rotary drying were much lower compared to the cost of electricity under microwave drying. The cost of natural gas consumption ranged from CANS 34.89 to CANS 52.33 per tonne of DDGS and accounted about 42 – 55% of the total drying costs. In booster drying, the unit costs of electricity and natural gas consumption were CANS 54.17 - 113.10 and CANS 24.64 – 36.97 per tonne DDGS, respectively. Both collectively accounted 56-71% of the total drying costs. In finish drying, electricity costs (CANS 17.27 – 33.79 per tonne DDGS) were lower and natural gas consumption costs were slightly higher (CANS 32.33 – 48.49 per tonne DDGS) than those obtained in booster drying.

Comparison between WDGS drying costs and historical DDGS market prices

Figure 7 compares the estimated drying costs under the various drying scenarios and drying system efficiencies of the 25 MLPY plant with the 2011-2013 average weekly market prices per tonne of DDGS.

Rotary hot-air drying, the base case scenario, had the lowest estimated drying cost per tonne of wheat DDGS. The estimated costs of using 100% microwave energy during drying, under both low and high drying system efficiency scenarios (depicted as first four bars of Fig. 7), were either equal or higher than the average historical market prices of DDGS. These indicate that use of 100% microwave energy during drying of wheat WDGS is not yet an economically viable option. The same can be said for booster drying, particularly under a low efficiency microwave drying system. Adding material cost and the costs associated with the other wheat DDGS processes, such as centrifugation, evaporation, and blending, may result to an overall wheat DDGS production cost that is higher than the average selling price. This would leave no or very little room for profit.

Microwave finish drying was seen as the most economically viable option among the three alternative scenarios. The costs of DDGS produced under this scenario were 37-59% lower than the historical market prices, the lowest among the three microwave-assisted drying scenarios. Introduction of microwave energy toward the end of the drying would increase the drying cost by about 11-15% and 15-20% compared to the use of conventional rotary hot-air drying in the 150 MPLY and 25 MPLY ethanol plants, respectively.

Lower costs of microwave finish drying were attributed to lower electricity costs per tonne of wheat DDGS since microwave energy was applied only towards the end of the drying process, thus resulting to lower electrical energy requirement compared to the levels observed in microwave and booster drying. However, this alternative drying scenario needs to be further assessed since the evaluation did not consider material cost and the costs of other wheat DDGS production processes. Incorporating these additional costs would enable a more comprehensive financial analysis of the costs and benefits of using microwave energy in drying wheat WDGS.
CONCLUSIONS
A techno-economic evaluation was conducted to assess the viability of incorporating microwave technology for drying wheat-based wet distiller’s grain with solubles (WDGS) in Saskatchewan ethanol plants. Three alternative scenarios (microwave, booster, and finish drying) were compared with the conventional hot air drying process (rotary drying). Two (low, high) and three efficiency (low, medium, high) levels were assumed for the rotary and microwave drying systems, respectively. Two ethanol plants, with 25 and 150 million liters of ethanol per year nameplate capacities, were used as models in the evaluation.

Use of microwave energy substantially reduced the energy requirement of the drying process. Under the given set of assumptions, it cannot completely replace the conventional hot air drying process yet because of high electricity cost. Estimated microwave drying costs were close to or higher than the historical market prices per tonne of wheat distillers dried grain with solubles (DDGS). Finish drying, which uses the least amount of electricity among the three scenarios, was seen as the more economically viable option of incorporating the use of microwave energy in an ethanol plant. A more comprehensive assessment of wheat DDGS production cost, however, is needed to provide a better estimate of the potential earnings under this scenario.

REFERENCES


Cellencor, Inc. n.d. (a). Transportable microwave test system. Ankeny, IA: Cellencor, Inc.


APPENDIX

Sample calculations
Techno-economic evaluation of drying wheat distiller’s grain with solubles using microwave energy.

Model Plant: 25 million liters per year (MLPY)
Scenarios:
- Rotary drying (base case, low efficiency)
- Microwave drying (scenario 1, high efficiency)

Mass flow rates:
Assumptions:

Calculations:
Amount of wheat DDGS produced/hour, \( m_d \)

\[
m_d = \frac{\text{Nameplate cap. * % utilization}}{\text{DDGS produced/ton of grain}} \times \frac{\text{Ethanol produced/ton of grain}}{\text{Annual operating hours}}
\]

\[
m_d = \frac{(25 \times 10^6 \text{ L}) \times 0.92}{8000 \text{ h}} \times \frac{370 \text{ kg}}{375 \text{ L}} = 2836.7 \text{ kg/h}
\]

Total amount of water to be evaporated

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Utilization, % of nameplate capacity</td>
<td>92</td>
</tr>
<tr>
<td>2. Annual operating hours</td>
<td>8000</td>
</tr>
<tr>
<td>3. Product generation from 1 t of wheat grain</td>
<td></td>
</tr>
<tr>
<td>a. Ethanol, L</td>
<td>375</td>
</tr>
<tr>
<td>b. DDGS, kg</td>
<td>370</td>
</tr>
<tr>
<td>4. Moisture content, % wet basis</td>
<td></td>
</tr>
<tr>
<td>a. WDGS entering the dryer</td>
<td>70</td>
</tr>
<tr>
<td>b. DDGS leaving the dryer</td>
<td>10</td>
</tr>
</tbody>
</table>

Amount of wheat WDGS entering drying system/hour, \( m_p \)

\[
m_p = \frac{(m_{DDGS} - m_{DDGS \times DDGS final moisture})}{1 - \text{WDGS initial moisture}} \times \frac{\text{Evaporation rate per unit area of dryer}}{\text{Annual operating hours}}
\]

\[
m_p = \frac{(2836.7 \text{ kg/h} - (2836.7 \text{ kg/h} \times 0.10))}{1 - 0.70} = \frac{8510.1 \text{ kg/h}}{5673.4 \text{ kg/h}}
\]

Total amount of water to be evaporated/hour, \( m_w \)

\[
m_w = m_p - m_{DDGS} = 8510.1 \text{ kg/h} - 2836.7 \text{ kg/h} = 5673.4 \text{ kg/h}
\]

Energy requirement:
Assumptions

Calculations:
Energy requirement under rotary drying

Total heat load, \( E_T \)

\[
E_T = m_pL_v + m_pC_p(T_f - T_i)
\]

\[
E_T = \left[ \frac{(5673.4 \text{ kg/h} \times 2260 \text{ kJ/kg})}{3600 \text{ s}} \right] \times \frac{1 \text{ h}}{3600 \text{ s}}
\]

Energy input for drying:

\[
E_{RD} = \frac{E_T}{c_D} = \frac{4851.6 \text{ kW}}{0.50} = 9703.2 \text{ kW}
\]

Energy requirement to be supplied by natural gas:

\[
E_{NG} = \frac{E_{RD}}{c_C} = \frac{9503.2 \text{ kW}}{0.85} = 11415.5 \text{ kW}
\]

Total energy requirement, \( E_T \):

\[
E_T = E_{NG} + E_{Electric motors} = 11415.5 \text{ kW} + 168.75 \text{ kW} = 11584.2 \text{ kW}
\]

Energy requirement under microwave drying:

\[
E_{m} = m_wL_v + m_pC_p(T_f - T_i)
\]

\[
E_{m} = \left[ \frac{(5673.4 \text{ kg/h} \times 2260 \text{ kJ/kg})}{3600 \text{ s}} \right] \times \frac{1 \text{ h}}{3600 \text{ s}}
\]

Energy input for drying (in applicator/ovens):

\[
E_{GD} = \frac{E_{m}}{c_A} = \frac{3713.4 \text{ kW}}{0.95} = 3908.8 \text{ kW}^*
\]

*This was later adjusted to 3950 kW to suit commercially available microwave generator sizes. See B.3.2, item 2d.

Energy requirement supplied from source to microwave generators:

\[
E_{S} = \frac{E_{GD}}{c_G} = \frac{3950 \text{ kW}}{0.85} = 4647 \text{ kW}
\]

Energy requirement under booster and finish drying:
This requirement is calculated by combining items 1 and 2 above. The only change is the amount of material to be dried under each drying method (rotary and microwave drying).

Equipment size and number:

Size and number of rotary dryers

Area of rotary dryer required, \( A_{RD} \)

\[
A_{RD} = \frac{\text{Amount of water to be evaporated/ hour}}{\text{Evaporation rate per unit area of dryer}}
\]

\[
A_{RD} = \frac{5673.4 \text{ kg/h}}{14.64 \text{ kg/h/m}^2} = 387.53 \text{ m}^2
\]

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Temperature of WDGS entering the drying</td>
<td>80</td>
</tr>
<tr>
<td>2. Product temperature during drying, °C</td>
<td></td>
</tr>
<tr>
<td>a. Rotary drying</td>
<td>250</td>
</tr>
<tr>
<td>b. Microwave drying</td>
<td>100</td>
</tr>
<tr>
<td>3. Rotary drying-related efficiencies</td>
<td></td>
</tr>
<tr>
<td>a. Dryer thermal efficiency, ( e_D )</td>
<td>0.50</td>
</tr>
<tr>
<td>b. Combustion efficiency, ( e_C )</td>
<td>0.85</td>
</tr>
<tr>
<td>4. Microwave drying-related efficiencies</td>
<td></td>
</tr>
<tr>
<td>a. Applicator efficiency, ( e_A )</td>
<td>0.95</td>
</tr>
<tr>
<td>b. Generator efficiency, ( e_G )</td>
<td>0.85</td>
</tr>
</tbody>
</table>

Dryer length (L), if diameter (D) is 2.4 m

\[
L = \frac{A_{RD} \pi D}{\pi (2.2 \text{ m})} = 56.07 \text{ m}
\]
Number of rotary dryers, $N_{RD}$

Commercial size chosen: 2.4 m x 20 m

$N_{RD} = \frac{\text{Required dryer length}}{\text{Commercially available length}} = \frac{56.07 \text{ m}}{20 \text{ m}} = 3 \text{ units}$

**Size and number of microwave drying units**

Energy requirement at the microwave applicators/ovens:

$$E_g = \frac{E_g}{S_A} = \frac{3713.4 \text{ kW}}{0.95} = 3908.8 \text{ kW}$$

No. of microwave drying units:

- No. of 1 MW units: $3908.8 \frac{\text{kW}}{1000 \text{ kW}} = 3$
- No. of 800 kW units: $908.8 \frac{\text{kW}}{800 \text{ kW}} = 1$
- No. of 150 kW units: $108.8 \frac{\text{kW}}{150 \text{ kW}} \approx 1$

Total energy supplied = 3950 kW

No. of microwave generators:

- No. of 100 kW generators = $\frac{3800 \text{ kW}}{100 \text{ kW}} = 38$
- No. of 75 kW generators = $150 \frac{\text{kW}}{75 \text{ kW}} = 2$

Total No. of microwave generators = 40

No. of waveguide assembly units = No. of generators = 40

No. of applicators/ovens:

No. of ovens = $\frac{\text{No. of generators}}{\text{2 generators per oven}} = 40 \div 2 = 20$

**Equipment costs**

Assumptions

**Calculations**

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Installation cost, % of purchase price</td>
<td>40</td>
</tr>
<tr>
<td>Foreign exchange rate, US$: CAN $</td>
<td>1:1.03</td>
</tr>
<tr>
<td>Cost of microwave</td>
<td></td>
</tr>
<tr>
<td>1 MW unit</td>
<td>$1,200,000.00</td>
</tr>
<tr>
<td>75 kW unit</td>
<td>$150,000.00</td>
</tr>
<tr>
<td>Rotary drying unit</td>
<td></td>
</tr>
<tr>
<td>Dry gas factor (direct contact), $f_g$</td>
<td>0.12</td>
</tr>
<tr>
<td>Material factor (stainless steel), $f_m$</td>
<td>1.4</td>
</tr>
<tr>
<td>Annual interest rate, %</td>
<td>15</td>
</tr>
<tr>
<td>Economic life, L, years</td>
<td>10</td>
</tr>
<tr>
<td>Salvage value, $S_V$</td>
<td>0</td>
</tr>
<tr>
<td>Annual operating hours, t</td>
<td>8000</td>
</tr>
<tr>
<td>Other costs:</td>
<td></td>
</tr>
<tr>
<td>US sales tax</td>
<td>4%</td>
</tr>
<tr>
<td>Canada custom duties</td>
<td>8%</td>
</tr>
<tr>
<td>Canadian GST</td>
<td>5%</td>
</tr>
<tr>
<td>Freight cost per mile</td>
<td></td>
</tr>
<tr>
<td>Within USA, USS</td>
<td>2.56</td>
</tr>
<tr>
<td>Within Canada, CANS</td>
<td>2.99</td>
</tr>
<tr>
<td>Equipment cost capacity factor, $x$</td>
<td>0.60</td>
</tr>
<tr>
<td>Distance (New Orleans, LO to Unity, SK), miles</td>
<td>2245</td>
</tr>
</tbody>
</table>

Initial cost of the microwave drying units:

- Cost of 3 – 1 MW units $\frac{\text{US $12,000,000}}{\text{unit}} \times 3 \text{ units} = \text{US$ 3,600,000}$
- Cost of 950 kW unit, $I_{950}$
- $I_{950} = I_2 - (Q_x/Q_2)^x$
- $I_{950,WM}=1200000*(0.95\text{MW}/1\text{MW})^{0.6} = \text{US$1,163,631}$

Total, in CAN$:

- $C_{MD} = (\text{US$ 36,000,000+116361)} \times 1.03 \text{ CAN$} = \text{CAN$ 4,906.541.00}$

Initial cost of the rotary drying units:

- $C_{RD} = 1.218(1+f_g+f_m) \times \text{exp(4.9504 - 0.5827 ln}(A_s) + 0.0925 (\ln(A_s))^2)$, 1000 US$
- A_s = \text{dryer lateral surface area, sq. ft} = 1622.33$
- $C_{RD} = \text{US$ 914,707.74}$, 3 units (see B.3.2 item 1d)
- $C_{RD} = \text{US$ 2744123.21}$

Other costs (calculations for microwave drying units only): Freight costs:

- Transporting microwave drying units from the US to SK using 40 ft container vans)

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of ovens needed</td>
<td></td>
</tr>
<tr>
<td>length of van/length of oven +20% allowance</td>
<td>$20 \text{ ft} / 12 \text{ ft}$ \times 1.20 = 8</td>
</tr>
<tr>
<td>Freight cost=Cost per mile $\frac{\text{no. of miles (return)}}{\text{van}} \times \text{no. of vans}</td>
<td>$\text{CANS 74,185.34}$</td>
</tr>
</tbody>
</table>

US sales tax, Canadian custom duties and GST:

- Sales tax and custom duties =
  - Initial cost (US $) * US sales tax $\frac{1.03 \text{ CAN$}}{1 \text{ US$}}$
  - + initial cost (CANS) * Canadian custom duties & GST rate
- Sales tax and custom duties = CANS 828,395.61

Installation cost:

- Installation cost = Initial cost * 40% = CANS 1,962,616.40
- Total equipment cost, $C_E$ (microwave drying):
  - $C_E = \text{Initial cost of equipment + other costs + installation cost}$
  - $C_E = 4,906,541.00 + (74,185.34 + 828,395.61)$
  - + 1,926,616.40 = CANS 7,771,738.35

Depreciation cost per hour, $C_{DEP}$ (microwave drying):

- $C_{DEP} = \frac{(C_E-S_V)(1+i)}{L_E*\text{t_a}} = \frac{(7771738.35 - 0)*1.15}{10*8000} = \text{CANS 111.72}$
Operating costs

Assumptions

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity, CANS per kWh</td>
<td>0.082</td>
</tr>
<tr>
<td>Cooling water</td>
<td></td>
</tr>
<tr>
<td>Cost, CANS per m³</td>
<td>0.6201</td>
</tr>
<tr>
<td>Tax rate, %</td>
<td>7</td>
</tr>
<tr>
<td>Consumption, L/min per generator</td>
<td>30</td>
</tr>
<tr>
<td>Natural gas, US$ per million BTU</td>
<td>3.70</td>
</tr>
<tr>
<td>Magnetron replacement</td>
<td></td>
</tr>
<tr>
<td>Life, h</td>
<td>8000</td>
</tr>
<tr>
<td>Cost, including freight and taxes, CANS</td>
<td>75 kW</td>
</tr>
<tr>
<td></td>
<td>100 Kw</td>
</tr>
<tr>
<td>General maintenance, % of purchase price</td>
<td>2</td>
</tr>
<tr>
<td>Personnel</td>
<td></td>
</tr>
<tr>
<td>Number of personnel</td>
<td>10</td>
</tr>
<tr>
<td>Average annual salary, CANS</td>
<td>90,000</td>
</tr>
<tr>
<td>Share of process in salaries, % of total</td>
<td>10</td>
</tr>
<tr>
<td>Training, CANS per person per year</td>
<td>1800</td>
</tr>
</tbody>
</table>

Calculations

Operating costs for microwave drying, CANS/hour

Electricity, C_P

Power required from main supply line = 4647 kW

\[ C_P = \frac{4647 \text{ kW} \times \text{CANS 0.082}}{\text{kWh}} = \text{CANS 381.06} \]

Water, C_W

\[ C_W = \frac{30 \text{ Lpm}}{1000 \text{ L}} \times \frac{1 \text{ m}^3}{\text{L}} \times \frac{\text{60 min}}{1 \text{h}} \times \frac{\text{CANS 0.6201}}{\text{m}^3} \times \frac{2 \text{ generators}}{\text{1.07}} \]

\[ C_W = \text{CANS 50.40} \]

Magnetron replacement, C_M

\[ C_M = \frac{N_{75kW} \times U_{75kW} + N_{100kW} \times U_{100kW}}{t} \]

\[ C_M = \frac{2 \text{ units} \times \text{CANS 8845} + 38 \text{ units} \times \text{CANS 9806}}{8000 \text{ h}} \]

\[ C_M = \text{CANS 48.24} \]

General maintenance cost, C_GM

\[ C_GM = \frac{0.02 \text{ Initial equipment cost}}{t} \times \text{CANS 4,906,541.00} \]

\[ = \text{CANS 17.17} \]

Personnel salaries and training cost, C_S&T:

\[ 0.10 \left( 10 \text{ employees} \times \text{CANS 90000} \right) \]

\[ + \left( 10 \text{ employees} \times \text{CANS 1800} \right) \]

\[ C_S&T = \frac{8000 \text{ h}}{\text{CANS 13.50}} \]

Operating costs for rotary drying, CANS/hour

Cost of natural gas, C_{NG}

\[ \text{Energy to be supplied by natural gas} = 11415.45 \text{ kJ} \cdot 1 \text{s} \]

\[ C_{NG} = 11415.45 \times \frac{\text{kJ}}{\text{s}} \times \frac{\text{US$ 3.70}}{\text{1 BTU}} \times \frac{1 \text{ BTU}}{\text{1.055 kJ}} \times \frac{\text{US$ 1}}{\text{1 h}} \times \frac{1}{\text{1 h}} \]

\[ = \text{CANS 148.45} \]

Other operating costs (electricity, general maintenance, and personnel salaries) are computed in the same manner as presented previously.

Converting cost per hour to cost/tonne:

\[ \text{Cost per tonne DDGS} = \frac{\text{Cost per hour}}{\text{kg of DDGS produced}} \times \frac{1000 \text{ kg}}{1 \text{ tonne}} \]

Depreciation cost per tonne DDGS

\[ = \frac{\text{CANS 111.72}}{\text{hour}} \times \frac{\text{hour}}{1000 \text{ kg}} \times \frac{2836.7 \text{ kg DDGS}}{1 \text{ tonne}} \]

\[ = \text{CANS 39.38} \]

Cost Summary

<table>
<thead>
<tr>
<th>Cost component</th>
<th>Drying cost, CANS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rotary (Base case, low efficiency)</td>
</tr>
<tr>
<td>Per hour</td>
<td>Per tonne DDGS</td>
</tr>
<tr>
<td>Depreciation</td>
<td>63.96</td>
</tr>
<tr>
<td>Electricity</td>
<td>13.84</td>
</tr>
<tr>
<td>Water</td>
<td>-</td>
</tr>
<tr>
<td>Magnetron replacement</td>
<td>-</td>
</tr>
<tr>
<td>Natural gas</td>
<td>148.45</td>
</tr>
<tr>
<td>General maintenance</td>
<td>49.46</td>
</tr>
<tr>
<td>Personnel</td>
<td>11.25</td>
</tr>
<tr>
<td>Total cost</td>
<td>286.96</td>
</tr>
</tbody>
</table>