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Research article

Towards an energy-friendly and cleaner solvent-extraction of vegetable oil

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ABSTRACT

The extraction of vegetable oils is an energy-intensive process. It has moreover a significant environmental impact through hexane emissions and through the production of organic-loaded wastewater. A rice bran oil process was selected as the basis, since full data were available. By using Aspen Plus v8.2 simulation, with additional scripts, several improvements were examined, such as using heat exchanger networks, integrating a Vapor Recompression Heat Pump after the evaporation and stripping, and examining a nitrogen stripping of hexane in the rice bran meal desolventizing unit followed by a gas membrane to recover hexane. Energy savings by the different individual and combined improvements are calculated, and result in a 94.2% gain in steam consumption and a 73.8% overall energy saving. The power consumption of the membrane unit reduces the overall energy savings by about 5%. Hexane separation and enrichment by gas membranes facilitates its condensation and re-use, while achieving a reduction of hexane emissions by over 50%. Through the considerable reduction of required steam flow rates, 61% of waste water is eliminated, mostly as organic-loaded steam condensate. Through overall energy savings, 52% of related CO_2 emissions are eliminated.

1. Introduction: the traditional oil seed extraction

1.1. Vegetable oils

Vegetable oils (soya bean, peanut, palm, sunflower, …) are parts of our common food commodities. Some however find new applications in biodiesel or even bio-aviation fuel through *trans*-esterification and associated secondary transformation processes (Alam et al., 2014; Issariyakul and Dalai, 2014; Lin et al., 2009; Wang et al., 2017; Yun et al., 2013; Cargill, n.d.; LIVESTRONG.COM, n.d.; NDTV-Food, n.d.). Other vegetable oils, such as rice bran oil (RBO), sheanut butter or palm kernel oil, are however mostly used in specific value-added markets of cosmetics, pharmaceuticals, and others (Cargill, n.d.; LIVESTRONG.COM, n.d.; NDTV-Food, n.d.). Despite the different end application, vegetable oil is produced either by extrusion/pressing at small to moderate capacities or by solvent extraction of pre-treated oilseeds, usually with hexane as solvent and/or with solvent/oil mixture (miscella) in the first stages of the extraction (Carrín and Crapiste, 2008; Cerutti et al., 2012; Martinho et al., 2008). To produce solvent-free products (oil, cake), the solvent needs to be removed from the miscella, oil and oilseed cake in evaporators and meal desolventizer/toaster, respectively. The recovered hexane is re-used in the leaching process. Significant quantities of steam and cooling water are used, mainly in the solvent recovery section of the process. Since their related operating costs represent up to 25% of the overall production cost, reductions in steam and cooling water consumptions are hence important economic targets in improving solvent extraction plants. Further improvements focus the degree of hexane recovery, the abatement of hexane emissions and the downsizing of the wastewater treatment plant using appropriate and novel technologies.

1.2. Process description

The oil processing of oil seeds such as corn, sunflower seed, rice bran, cottonseed and peanut, is similar to soya beans, and typically consists of oilseed handing, seed flaking prior to solvent extraction, oil extraction and desolventizing, cake (meal) desolventizing, and oil refining. Solvent is recovered and re-used (Cerutti et al., 2012; Cheng et al., 2018; Martinho et al., 2008; US-EPA, n.d.;

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FoodTechInfo.com, n.d.). Together with the energy-intensiveness, considerable emissions of particulate matter and volatile organic compounds (hexane) occur. Hexane emissions are due to the supply and storage of hexane on site as well as to diffusive losses from e.g. wastewater aeration, piping, pumps, valves and vents. Small quantities of hexane ($\leq$0.2 vol% of oil) remain in the crude vegetable oil. Trace quantities are present in the waste water collected from the condensation of steam (the solubility of hexane in water is 0.014%). The vegetable oil extraction process is summarized in Supplementary Information S1, based on the detailed description of the current process, with all successive steps, as provided by e.g. the United States Environmental Protection Agency (US-EPA, n.d.) or by FoodTechInfo (FoodTechInfo.com, n.d.). Particulate emissions occur throughout the process and are abated using dust collection devices, currently mostly by cyclones. For the soya bean treatment, major emissions occur in the bean receiving (0.07 kg/t), cracking/dehulling (0.16 kg/t), hull grinding (0.09 kg/t), bean conditioning (0.005 kg/t), flaking (0.017 kg/t), flake and meal cooler/dryer (0.60 kg/t), meal milling and load-out (0.28 kg/t). These dust emissions can be reduced by nearly 90% when using more appropriate dedusting equipment, such as fabric or sintered metal fibre filters (Schildermans and Baeyens, 2006; Smolders and Baeyens, 2000). Waste water production (due to organic-loaded condensate) and hexane emissions need to be reduced.

1.3. Objectives of the research

Considering the energy and environmental drawbacks of the traditional process, the research had 6 main objectives: (i) to assess the operation data of a small-scale RBO mill, used as example of the traditional vegetable oil production process; (ii) to simulate the RBO process using Aspen Plus v8.2 software, complemented with own data and additional Matlab scripts, and to compare plant and simulated data; (iii) to examine possible energy savings within the steam/cooling water circuits by integrating heat exchanger networks; (iv) to study a further reduction of the energy requirements by replacing steam with nitrogen in the meal desolventizing, while applying a gas membrane for hexane recovery and emission abatement; (v) to propose an energy-friendly and clean process, as the result of the different improvement measures; and (vi) to assess the impact of these measures on a large scale soya bean oil extraction process.

2. The RBO process as case-study for potential process improvements

2.1. Generalities

The case-study RBO mill, located in the Heilongjiang Province of China, has a continuous production capacity of 1.33 t/hr RBO. The process flowsheet is illustrated in Fig. 1. A leaching conveyor extracts crude RBO by hexane. Miscella is subsequently subjected to a two-step evaporation to remove hexane. Residual solvent in the miscella is further removed by direct steam stripping. RB meal is thermally treated in a multiple hearth desolventizer-toaster. Solvent and water vapours are condensed in a multi-step cooling. Vapours are finally stripped of hexane by absorption in paraffin.

All essential data and operating conditions were collected at the plant and are given in Table 1. The flow rates include 5670 kg/h of defatted rice bran (RB) and 527–692 kg/h of H_2O. Specific extracted products are given in Table 2. The total flow rate is 7527–7692 kg/h. The total steam consumption of the plant is 2,400 kg/h, and 393 m^3/h of cooling water is used. The total energy consumption is 1768 kW.

The amount of hexane in the miscella after leaching is between 4122 and 5494 kg/hr. It is reduced to 587–913 kg/h in the miscella after the first evaporation stage and to below 70 kg/hr in the miscella after the second evaporation stage. Less than 4 kg/hr is present in the RBO. Hexane is recovered and re-used.

2.2. Simulation of the case-study RBO process and possible energy savings

Aspen Plus v8.2 is used as simulation tool for the defined components, using appropriate thermo-dynamical models and defined equipment and operating conditions (Yun et al., 2013). Additional subroutines were prepared and imported into the simulation for operations involving a solid phase. Within the components of RBO, a difference should be made between polar and non-polar compounds, hexane being the only non-polar one. For operation at a low pressure of 50 kPa–101 kPa, both a Non-random-two liquids model (for most of the RBO compounds, being polar) and the Peng-Robinson model (for hexane as non-polar component) were applied in the simulation. Details of the simulation package, including the inserted FORTRAN block for the leaching column, are described in Kong et al. (2015). The simulation assumes steady-state operations with all of the components entirely transferred into the meal-desolventizing (RB cake) and the 1st evaporator (oil and miscella), at given mass flow rates between inlet and outlet flow is calculated. Table 3 provides the simulation results, together with the plant real-time data.

Simulations reveal a steam consumption of 2,426 kg/h, within 2% of the real ~2,400 kg/h, and a cooling water use of 392.6 m^3/h, in full agreement with the plant data. This agreement confirms that the simulation approach by Aspen Plus v8.2 was appropriate and could further be applied to assess potential energy savings. Aspen Plus v8.2 was hence applied to study possible energy savings.

3. Energy saving options

3.1. Energy savings through integrated heat exchanger networks and Vapor Recompression heat pump

Pinch technology, as developed by Linnhoff and Hinmarsh (Linnhoff and Hindmarsh, 1983), is commonly applied to assess energy efficiency (Sun et al., 2015; Yun et al., 2013) and energy integration (Baeyens et al., 2015; Kang et al., 2014). It was not previously applied to the vegetable oil extraction process. Within the RBO process, the integration of heat exchanger networks was targeted, with algorithms entirely based upon pinch analysis (Kemp, 2007; Klemeš et al., 2013), with a minimum 10 °C temperature difference in the heat exchangers deemed acceptable. Fig. 2 illustrates the pinch energy optimization strategy for the selected cold and hot flows, according to details described in Kong et al. (2015). The hot powder flow of the meal desolventizing was excluded since present as solid matrix, and hence not readily for heat exchange with other streams. Input and output temperatures of the flows were taken from the simulation results of Table 3. The heat-transfer coefficients for the different flows were taken from Kemp et al. (Kemp, 2007). The enthalpy of each flow was calculated from the its specific heat and temperature difference from feed to outlet conditions.

Results are illustrated in Table 4 for the different units of the RBO process.

The steam consumption was reduced to 2091 kg/hr (against the simulated 2426 kg/hr in the current operation mode), i.e. by ~13%. The cooling water requirements were reduced from 393 to 354 m^3/hr, i.e. by ~10%. The heating and cooling requirements were reduced by respectively 206 kW and 612 kW. The maximum heat exchange integration capacity was 594 kW. Rice bran oil, like all vegetable