Recovery of low temperature heat in oil mills

Patrick CARRÉ

CREOL,
11 rue G. Monge,
33 600 Pessac,
France
<carre@cetiom.fr>

Abstract: *Energy consumption in oil mills is a major item of costs and a sensitive point in the production of biofuels. To improve their performance, industrials can recover low-temperature heat thanks to a new technology of heat exchangers suitable for treating granular solid materials. Information about the energy requirements of the rapeseed crushing being not readily available, the article gives a detailed assessment of consumption items (per ton of seed: 263 MJ for preparation operations and 284 MJ for solvent extraction). These exchangers used as pre-conditioners saves about 55 MJ.t⁻¹ of heat by use of steam condensates. We could go further in use of these devices on the one hand to recover heat from press cake and meal, and secondly to use recovered energy to dry and warm up the seeds before pre-pressing. In this configuration, the energy savings could reach 38% of current needs.*

Key words: *oilseeds, crushing, energy saving, heat transfer, rapeseed, drying*

Energy consumption, especially when the oilseeds are crushed for biodiesel production is an important issue for oil mill managers. Large corporations are not disclosing their performances but according to available information, one can evaluate the needs of thermal energy (electricity not included) between 500 and 900 MJ.t⁻¹ of crushed seeds. A significant part of this energy which is dissipated during cooling of the output streams could be recovered. This recovery is only possible if an efficient heat exchanger can transfer this heat to the seeds entering in the oil mill. In recent years, an OEM offers exchangers with large exchange surfaces enabling the implementation of these heat recoveries. After recalling the details of the energy needs in crushing process, this article presents and discusses the potential use of these new exchangers applied to rapeseed oil extraction.

Thermal energy consumption in crushing industry

The needs assessment of the theoretical heat required for different stages of crushing must take into account the specific heats of seeds, oilcakes, meal and oil. The available values are relatively rare, often old and vary quite widely. *Table 1* shows some thermal values from the literature.

Values used in this study : 1.9 kJ.°C⁻¹.kg⁻¹ for seeds and meals, 2 kJ.°C⁻¹.kg⁻¹ for oil, 2.27 kJ/kg for hexane, latent heat of vaporization of hexane: 328 kJ/kg, boiling point of hexane 69 °C (Linde, 2009). Characteristics of seeds and meals: in this study, seeds were considered having a water content of 7.8% and an oil content of 45.0%. These values represent the average outcome of CETIOM's investigation ''rapeseed crop quality'' between 2007-2011 (Garnon, 2011). Meal, according to the last issue of the survey of the French organization for oilseeds (2011) have average water content of 11.3% and an oil content of 2.7% (± 0.5) in the year 2011 (Peyronnet and Dauguet, 2012). It was considered for the press cake an oil content of 21%. Products flows and material balance are shown in the *figure 1*.

Processing steps

Seeds were submitted to several processing steps involving changes in temperature, moisture and oil content. The process was divided into two main parts: mechanical extraction and solvent extraction.

Mechanical extraction

Thermal conditioning

This step is not mandatory but is applied in most crushing units. Seeds are preheated prior to flaking at temperature of approximately 60 °C without significant change in water content. This preheating improves the plasticity of seeds and improves the formation of the flakes. Its main difficulty arises from the low thermal conductivity of rapeseed. According to Timbers (1975), the thermal conductivity of rapeseeds is in the range 0.10 and 0.15 W m⁻¹.°C⁻¹. In practice, this means that the seed acts as an insulating material. For comparison, these values are between the thermal conductivity of plywood (0.11 W.m⁻¹.°C⁻¹) and pine wood (0.15 W.m⁻¹.°C⁻¹). Conduction alone cannot heat a mass resting on a heating surface. It is therefore necessary to force convection by vigorous shaking of the seeds and a fairly large exchange surface is required to allow the heat exchange. For example, the *figure 2* relates the change in temperature measured by a thermocouple in a layer of 10 mm

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Table 1. *Some values about specific heats of the products handled in oil meals.*

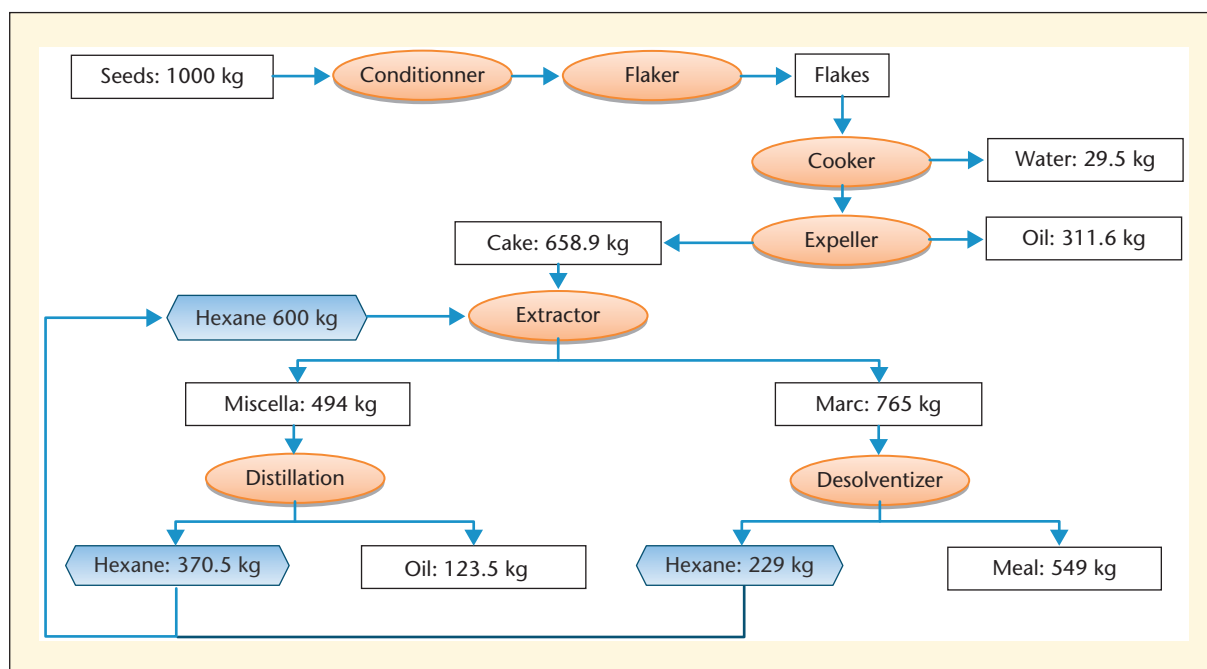| Product	Specific heat (kJ.°C^{-1}.kg^{-1})	Comments	Source
Flakes (rapeseed)	2,5	Values likely to be overestimated but taken in account at industrial level	(Laisney, 1984)
Oils	2,3		(Laisney, 1984
Soybeans	$1,20 + 0,042.H + 0,005.T$	C = 1,83 Water: 8%, T°: 60 °C	(Berthon, 1977) (Berthon, 1977)
	$1,444 + 0,059.H$	C = 1,91 Water: 8%, T°: 42 °C	(Deshpande & Satish, 1999) Deshpande & Satish, 1999)
	$1,593 + 0,0259.H$	C = 1,81 Water: 8%, T°: not specified	(Alam & Shove, 1973) (Alam & Shove, 1973)
	$-101,1\ 0,12.H - 0,00013.H^2 + 0,63.T - 0,00097\ T^2 - 0,00032.HT$	T° in K 1.90 at 8% water and 60 °C	(Aviara, *et al.*, 2011) Aviara, *et al.*, 2011)
Rapeseed	2,68	Water: 11%	(Srours, 1982) (Srours, 1982)
	$1,287 + 0,067.H$	1,82 at water: 8% Variable/cultivars ± 0,13)	(Timbers, 1975) (Timbers, 1975)
	$1,356 + 0,032.H$	T°: 19 °C 1.61 at 8% water	(Moysey, *et al.*, 1977) (Moysey, *et al.*, 1977)
	$1.265 + 0.03.H + 0.00575.T$	1.85 at water: 8%, T°: 60 °C	(Muir & Sinha, 1986) (Muir & Sinha, 1986)
	2,10 à 3,12	(article in Turkish language)	(Kocabiyik & Tezer, 2007) (Kocabiyik & Tezer, 2007)
Sunflower seeds	5,57 ± 1,2 (2s)	Water: 9.7% T°: 80 °C.	(Ilori, *et al.*, 2011) (Ilori, *et al.*, 2011)
Rapeseed oil	1,96	T°: 20-30 °C	(Joly, 1982)
Soybean oil	$1,75 + 0,0029.T$	2,04 T°: 100 °C	(Joly, 1982)

H: water content % ; T: temperature (°C)

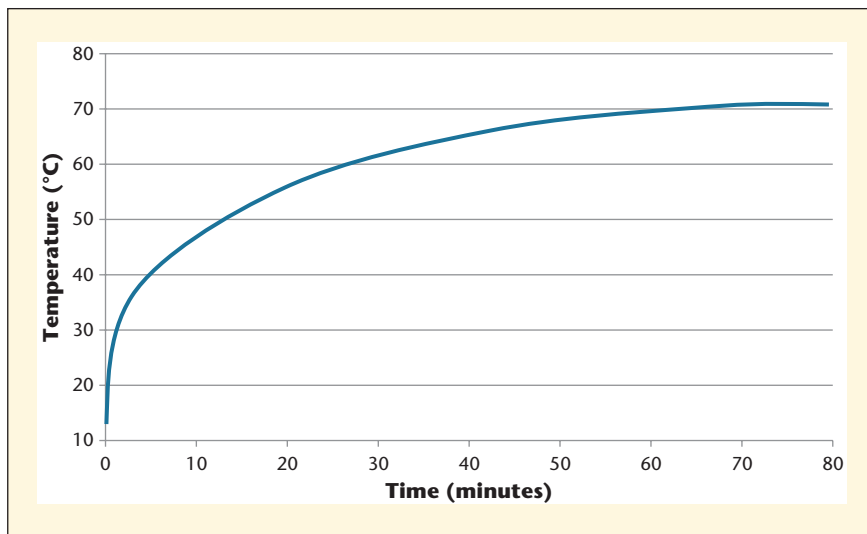Figure 1. *Mass flows during rapeseed processing.*

Figure 2. *Evolution of the temperature in the center of a 10 mm layer of cold rapeseed between two masses of rapeseed at 72 °C (CREOL, unpublished data).*

rapeseed initially at 15 °C between two layers of seeds at 72 °C. It shows that half an hour is necessary to reach 60 °C at 5 mm from the warm seeds.

An indirect consequence of this difficulty is the need to keep the seeds for a relatively long time in conditioners and because it is accompanied by vigorous stirring, the mixing is an important cause of residence time dispersion.

Flaking and conveying

Flaking by itself does not significantly modify the temperature of the material, however, transport between the conditioner, flakers and cookers allows significant heat loss which varies according to the length of the circuits and their ability to dissipate heat. The magnitude of these losses was estimated to 5 °C.

Cooking

Cooking flakes improves the capacity of presses to extract the oil and produce oilcakes with favorable characteristics to subsequent extraction steps. The three main effects of cooking are: 1) a reduction in the viscosity of oil allowing it to flow better through the cake (Darcy's law), 2) a coagulation of interfacial proteins leading to the destabilization of oilbodies to increase oil availability and 3) a more or less important drying action resulting in a final water content of between 4 and 6% in flakes. Water acts as a plasticizer in the cake, reducing its ability to oppose the force of screws which leads to less important pressures in wet conditions and a weak deoiling performance. A loss

of 29.5 kg of water per ton of crushed seeds was considered in the case study (7.9% to 5.0% water in flakes).

Expelling

The principle of mechanical extraction is to maintain the solid matrix in a cage designed to let liquid flow and strong enough to resist to high mechanical force exerted by a rotating screw pushing the solid across constantly reduced volumes. The mechanical work of the screw is degraded into heat which raises the temperature of the cake and to a lesser extent the one of the oil.

Clarification of the press oil

Before being stored, the oil should be filtered or clarified by centrifuge decanting. These treatments do not require supplementary heating of the oil.

Cake Granulation

Granulation is not systematic, but rapeseed cake produced by high-speed high-capacity screw presses often exhibits characteristics that are not optimal for solvent extraction, especially when said extractors are not compartmentalized and allow horizontal circulation of miscellas when its vertical percolation is slow. Indeed, for making an effective countercurrent extraction, the solid material must have two qualities: good extractability of oil and a homogeneous and relatively fast percolation of liquid through thick layer. The extractability assumes that the solvent can dissolve the oil enclosed inside the cake particles. Two obstacles may occur: a defect of milling corresponding to a lack of cells

disruption and a defect of permeability corresponding to the smoothing and compacting of the surface by the press. Well controlled granulation produces pellets with favorable solvent absorption and offer perfect percolation characteristics. This effect is not guaranteed because granulation can also reduce the permeability of the cake to hexane. In practice, it is rather for its effect on the regularity of the percolation that granulation was adopted. Another benefit is an improvement in cake density that has the effect of improving the capacity of extractors.

Pellets cooling

The pellets come out at a temperature in the range 105 and 115 °C. They cannot be sent directly to the extraction because their high temperature generates a risk of vaporization of the solvent. Cooling is done by blowing air through the cake. The goal is to reduce the temperature at the higher level compatible with the safety of the plant. For our study, we considered 80 °C.

Countercurrent extraction and solvent regeneration

Pellets, cake, collets or flakes are extracted by percolation of hexane in countercurrent extractors. The extraction temperature is a compromise between the necessity to take advantage of the positive effect of heat on extraction rate and the rise of solvent losses near to boiling point (Baumeler, *et al.*, 2010). In practice, this temperature can vary from 45 to 60 °C. A value of 55 °C was used in the assessments of this study.

The solvent enters in the extractor at a temperature close to 40 °C. A concentration of oil in miscella of 25% and retention of hexane by the marc of 30% were considered in our assessments. This requires the use of about 600 kg of solvent per ton of crushed seeds. In reality, the hexane content of the marc is dependent on the type of extractor and quality of the cake (granulation). For thick layer extractors (3 m) with non-granulated cakes, impregnations may exceed 35%, while values below 25% can be observed in thin layer extractors (< 1 m) on pelletized cakes. Regarding the concentration of miscellas, it is possible to achieve much higher concentrations. Laisney in ''L'Huilerie Moderne'' shows concentrations of 38% (Laisney, 1984).

Table 2. *Summary of the heat consuming operations in rapeseed crushing (per ton of seeds).*

Step	Material	Change	Heat required (MJ.t^{-1})	Steam consumption (MJ.t^{-1})
Conditioning	Seeds	T°: 15 → 60 °C	78	36.6
Cooking	Flakes	T°: 55 → 105 °C	110	53.4
		Vaporization of 30kg of water	66	32.2
	Air (dry) for drying	T°: 20 → 100 °C	8	3.9
Total preparation			263	126
Desolventization	Meal	T°: 55 → 105 °C	52	26.1
	hexane	T°: 55 → 69 °C	8	3.9
		Vaporization	75	37.6
	Steam	Sparged	77	27.5
		Condensed	38	13.5
Distillation	Miscella	T°: 55 → 69 °C	8	2.7
	Oil	T°: 69 → 110 °C	10	3.6
	Hexane	Vaporization	122	58.9
Enthalpy supplied by the gas from the DT			−104	−48.9
Total extraction			284	125
Losses (5%)			27	12.5
Total preparation + extraction			574	264

Desolvation of marc

After extraction, the solvent from which the marc is impregnated must be removed by indirect heating and direct steam injection. Indirect heating is obtained by forcing the material to contact a tray heated by steam which is condensed in a double jacket located under the tray. Direct steam is injected countercurrently in the lower trays of desolventizer. Direct steam has two effects: it brings large amount of heat by condensation when it encounter the relatively cold marc and it decreases the concentration of hexane vapors in desolventizer atmosphere, a desaturation allowing the final desorption of the solvent in the bottom trays. The amount of direct steam to be used is modulated to reach a temperature of 70 °C in the vapors leaving the desolventizer (Schumacher, 1983). According to Schumacher, 0.12 kg of steam per kg of hexane is required to reach this temperature. Desolventizers technology has evolved over time; major changes have focused on the management of predesolventization and steam injection. According to the devices designs, we can observe a certain disparity in the mass of condensed water in the meal. Generally, there is an excess of water in the meal requiring a drying treatment downstream. In some new desolventizers, direct steam condensation is reduced by separating the vapors stemming from the desolventizer of the pre-desolventizing part of the device. One of the reasons that led to this evolution is the necessity to reduce the loss of protein solubility due to the wet cooking. Nevertheless, there are still many desolventizers with just one steam outlet and, in many plants; this operation is a bottleneck that requires the operator to use the equipment in sub-optimal conditions in order to cope with the constraint on the solvent conservation. In consequence, the real consumption of steam for the meal desolventization may represent higher figures than given in *table 3*. As explained above, the largest cause of over-consumption is due to condensation of direct steam leading to an excess of water content in the meal. The enthalpy of vaporization of condensed steam is lost during the drying step. In the present study, it was considered that we just consumed the amount of direct steam required to reach 11.5% of water in meal.

Miscella distillation and heat recovery from the desolventizer

The gases exiting the desolventizer pass through an exchange column to recover the condensation heat and evaporate a portion of the miscella. This exchange, according to Anderson (1989), allows ensuring that 75% of the heat necessary for distillation of the miscella is provided by the vapors leaving the DT. On the basis of our case study values, distillation requires 139 MJ/t of seeds from which 104 MJ are supplied by the vapors of the desolventizer. Distillation uses direct steam in ejectors to generate some vacuum and to help stripping the solvent residues but these flows are partially recovered and it was considered that they were included in the residual 25%.

The real values vary according to the amount of steam condensed in desolventizer and the performance of the heat recovery for the miscella pre-concentration. As explained in the introduction, the industrial data are not accessible but the presented figures were assessed by careful recoupment of available information and use of conservative hypothesis. They can be regarded as reasonably accurate valuation of the real consumptions of the most efficient oil mills given that on average, the actual values are more frequently at higher levels *(figure 3)*.

Production of heat by condensation of high pressure steam and low-temperature heat

In oil mills, the main thermal vector in use is 10 bar saturated steam. The heat transfer is made when steam is con-
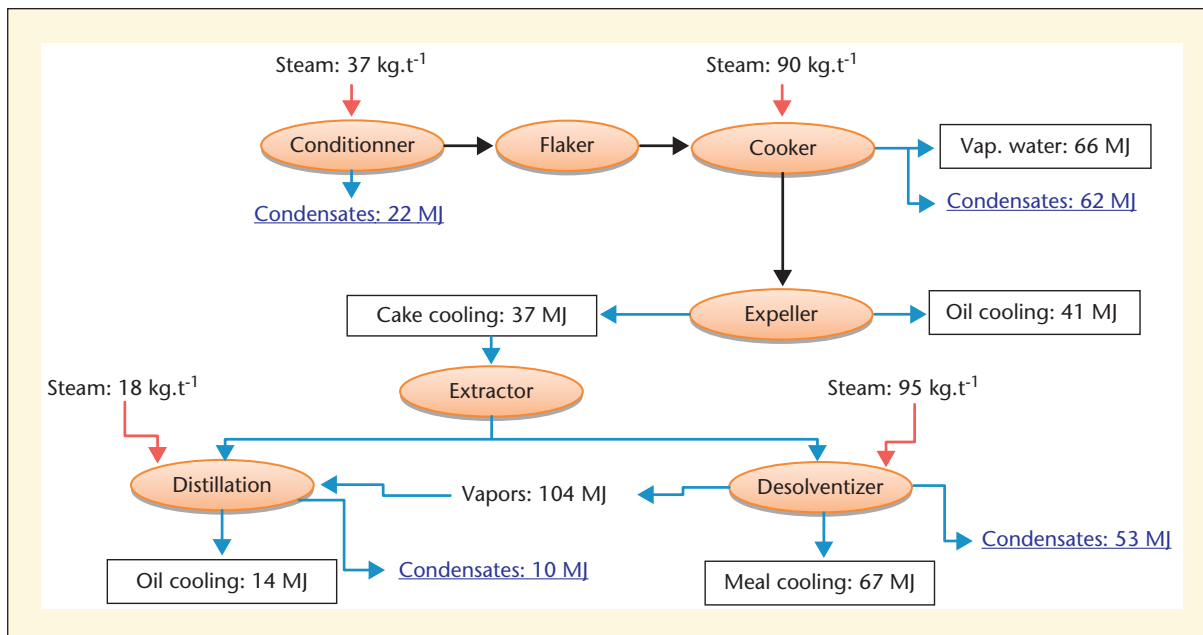
Figure 3. *Streams of recoverable heat in processing 1 t of seeds.*

densed in one side of the exchange surface to yield the water enthalpy of vaporization which is transferred to the heated material by conduction across the steel wall of the exchanger. Since the thermal conductivity of the solid materials is weak, a high differential of temperature is required to obtain satisfactory performance. On the side of steam, the temperature is the one of saturated water presented in *table 2*. When the condensates are purged, they go to a lower pressure which leads to partial revaporization. According to the data in *table 3*, around 70% of steam is used indirectly in heat exchangers. The residual enthalpy of condensates depends on the initial pressure so we considered an average value of 6 bars with 0.7 $MJ.kg^{-1}$ to be returned toward the boiler at 0 bars and 80 °C (0.33 $MJ.kg^{-1}$). Each kg of condensates can deliver 0.37 $MJ.kg^{-1}$. Considering that we could replace the pre-condi-

tioner by a low temperature heat exchanger, we would subtract the condensates previously produced by this device from the 185 kg of condensates of our valuation. With 150 kg of condensates, we can recover 55 $MJ.t^{-1}$ of seeds, *i.e.* 9.6% of the total needs of heat of the oil mill.

Other potential sources of low temperature heat

Oil from mechanical extraction and oil from solvent extraction go out of the system at temperatures close to 100 °C. Returning them to 35 °C could allow recovering 55 $MJ.t^{-1}$ of crushed seeds.

Water exiting the cooker could be condensed to recover 66 $MJ.t^{-1}$.

Cooling the cake before extraction from 110 °C to 80 °C could supply 37 $MJ.t^{-1}$.

Cooling the meal after desolventization could supply 67 $MJ.t^{-1}$.

In total 225 $MJ.t^{-1}$ could be saved provided that efficient heat exchanger could enable this recovery and that one has the possibility to use the recovered heat with its low temperature *(figure 3)*.

Opportunities for recovery of low temperature heat

Thermal conditioning of seeds before flaking is the point where low-temperature heat recovery is the most accessible given the laws that govern energy degradation in installations handling large quantities of material of poor thermal conductivity. Let us recall that the time required for heat transfer depends on both material conductivity and temperature difference between the hot source and the cold source. From a thermal fluid whose temperature is close to 100 °C, it is not possible,

Table 3. *Steam table.*

Pressure (bars)	Temperature (°C)	Latent heat of vaporization (kJ.kg⁻¹)	Liquid water enthalpy (kJ.kg⁻¹)	Steam enthalpy (kJ.kg⁻¹)
10	184	1999	781	2780
6	165	2065	703	2762
3	144	2133	605	2738
0 = ambient	100	2258	417	2675

unless multiplying the duration of the exchange, to warm up seeds at temperatures well above 60 °C. The constraint of low temperature difference requires increasing the exchange surface or mixing speed.

SOLEX technology: an innovative solution to improve the efficiency of heat recovery

Solex Thermal Science is a Canadian company founded in 1999 previously under the name Bulkflow Technologies. It has acquired a technology developed in the 80s to cool fertilizers (Mueller, 1992). The technology was subsequently improved and adapted for heating, cooling and drying bulk solids (Anonymous, 2008). The design of the Solex heat exchanger is based on a bank of vertical heating plates closely spaced to allow a downward flow of bulk material. The granular solid slides down against the plates within which a thermal fluid flows. The exchange takes place by conduction. On some models, drying is also possible by injecting air and extracting it at low speed between the plates. The shape of the plates allows to some extent to renew the layer of seeds in contact with the metal wall which promotes temperature uniformity. With systems sized to large capacity of modern mills (80 t.h^{-1}), several banks of plates are stacked which improves the homogeneity of outlet temperature. Applications are designed using thermal modeling software, which provides accurate product temperatures prediction, to obtain a guaranteed thermal performance (Forniciov, 2008).

The extraction system is adapted to allow a smooth flow avoiding preferential paths. In the case of oilseeds, in contrast to *figure 4*, the system is generally constituted by a screw whose core has a diameter decreasing for generating a constant volume in all areas of the device (Farr and Skold, 2012). Available exchange surface is much greater than in a traditional conditioner that allows the use of lower temperature thermal fluids while occupying a small volume. For conditioning grain before flaking, a capacity of 80 t/h requires a heating power of about 1600 kW. With a conventional vertical conditioner having superimposed plates of 4 m diameter, it takes about 12 stages to ensure the transfer of heat (personal valuation evaluation).
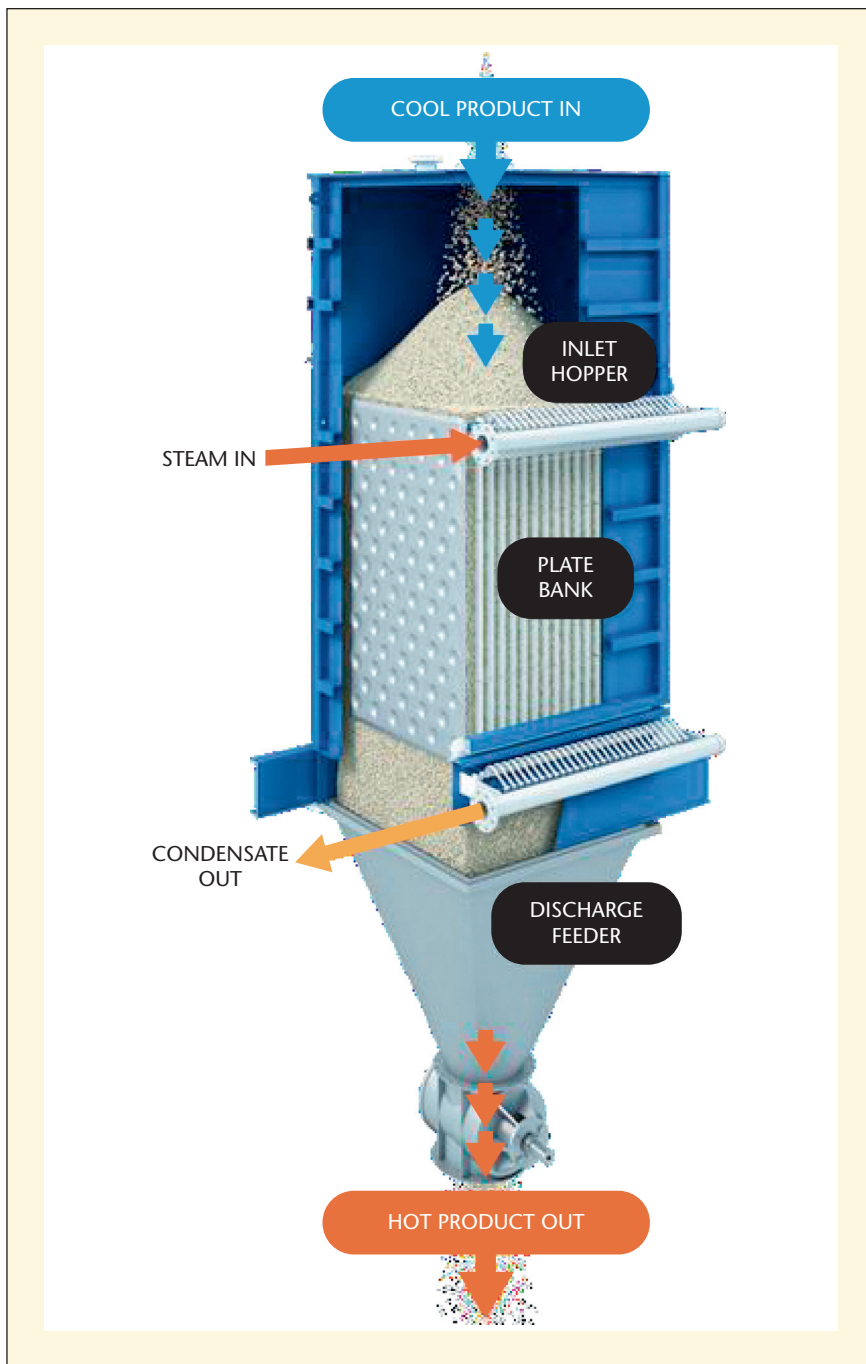

Figure 4. *General presentation of the Solex heat exchanger (Solex Cie, 2012).*

Assuming that each stage has height of 0.7 m, the occupied volume is in the order of 100 m^3. In a Solex exchanger, the power per unit of heating surface is strongly reduced because of the low-temperatures, but the possibility of accommodating a large number of plates per unit of volume allows making the heating in a volume of the order of 50 m^3 and a floor area excluding accessories of 5 m^2. Implementation of Solex exchangers in existing units is facilitated by this compactness.

Another advantage is the lack of mechanical mixing of seeds. Conventional systems are equipped with arms forcing the movement of seeds to bring them into contact with hot surfaces. In vertical conditioners, there is a central shaft on

which arms are welded which scrape the surface of the plates. Mechanically moving parts are a cause of inflated investment and electricity consumption.

The residence time in the apparatus for a preheating configuration is less than 20 minutes; the temperature of hot water required may be in the range 70 and 98 °C. For lower values, an increase in the heating surface is necessary. In terms of maintenance, the lack of moving parts reduces the frequency and the number of interventions.

These heat exchangers are very well suited to low-temperature heat recovery in plants crushing rapeseed. The theoretical amount of available condensates is not sufficient to supply the heat required, therefore, it is necessary to use extra steam to reach the desired temperature at flakers entry.

Potential advantage of the method for further energy saving

The ultimate means of heat recovery would be to use the waste heat to dry the grain mass. Conventional dryers are not very effective in evaporating water when the seed is already relatively dry. To understand the superiority of the Solex system over conventional dryers in the case of seeds at low water content, we must return to the principles of drying. In conventional dryers, the enthalpy of the air is given at the inlet heater and then this enthalpy will allow exchanging temperature against water vapor so that the exhausted air leaves the dryer close to the dew point temperature. In the case of relatively dry seeds, it becomes difficult to reach the point of saturation because the seeds are cooled by water evaporation when high temperatures are required to reach the high water activity necessary to saturate the drying air. In consequence, large amounts of heat are wasted to heat air that leaves the dryer far from being saturated. In the Solex heat exchanger, one does not heat the drying air but the solid material. By warming the solid before the air, the water activity rises first facilitating the water transfer. Moreover, the air temperature can be raised while its moisture content grows allowing increasing water load by unit of air mass. For this reason, the mass of air required to dry the seeds is significantly reduced.

For example, dry rapeseed from 8 to 5%, is equivalent to extracting 3.15 kg of water per 100 kg of seeds. With a conventional dryer using air at 20 °C and 70% of relative humidity, heating this air up to 65 °C and leaving it at 80% of relative humidity, there is the possibility of carrying 12 g of water per kg of air for an energy cost of 45 kJ. Therefore one must spend 11.7 MJ to dry 100 kg of seeds. In the system where the grain is warmed by conduction at 80 °C, if the air leaves at 70 °C with a relative humidity of 70%, one kg of air can carry 170 g of water. The energy cost per kg of air is 420 kJ.kg^{-1}, thus the expense per 100 kg of seeds is 7.8 MJ. The difference in energy cost is not huge but the heat used could come, at least partially from low-temperature thermal fluid.

The problem for applying this heat recovery is that drying seeds before flaking would result in dusty flakes and poorly efficient downstream cooking and expelling. In the normal process, the temperature rises when the seeds are still wet and drying occurs only in the lower stages of the cooker. In consequence, the flakes are encountering wet heat during the process which is more efficient to coagulate the proteins. If the seeds were just heated after drying, it is possible that oil extractibility remains low.

In our experience, tests carried out in CREOL pilot plant showed that the flakes cooked using the standard protocol after drying were not suitable for the mechanical extraction. We performed additional experiments to determine what would be the most favorable technical route for the treatment of pre-dried seeds. The best results were obtained by introducing into the press seeds heated to 80 °C without flaking. According to this work, energy consumption of the press remained close to that of the reference having undergone classical conditioning and cakes pressure obtained in this way had better extractability (residual oil in the cake 1.7% vs 2.6%). In accordance with the objectives of this study, the desolventization of the meal was easier in the case of pre-dried seeds resulting in meals with higher protein solubility (Quinsac, et al., 2011). The possibility of removing the flaking step would simplify the technical route, saving investment, maintenance and energy. This promising work has not been confirmed yet.

Considering that this new processing scheme could be implemented by use of Solex heat exchanger using low-temperature thermal fluids to heat the seeds up to 80°C and evaporating around 30 kg of water per ton of seeds, the need of heat per ton of seeds would be in order of 200 MJ. On the supply side, the condensates would be sharply reduced with the elimination of the cooker and no more than 10 MJ.t^{-1} would be available. The heat from the evaporated water would be difficult to recover so it was not taken in account. The temperature of the cake could also be reduced, resulting in lower amount of heat to recover (18 MJ.t^{-1} of seeds). The other streams are not modified, so the available heat for re-use is now: 150 MJ. The residual need of heat becomes 50 MJ.t^{-1}, i.e. 25 kg.t^{-1} of steam.

Finally, from 126 kg of steam per ton of seed, the need for preparation before pressing could fall by about 100 kg. Overall consumption of crushing unit could go from 264 to 160 kg of steam per ton of grain: a saving of 38%.

Conclusion

Solex exchangers currently used to preheat seeds before flaking make theoretical possible reductions in energy consumption equivalent to 30-40 kg of steam per ton of crushed seed but there are not enough steam condensates available to perform that saving and the real figure is below 10% of the steam consumption. In addition to this interest, using these new exchangers can gain significant place in the environment of older plants where space is limited and they have reduced power needs compared to old conditioners. Another advantage is to use a low temperature thermal fluid which prevents overheating of seed in case of downstream problems which immobilizes the seeds in the exchanger. The main concern is relative to flow problems that could occur in the presence of impurities or large sticky residue accumulation in some areas. According to Solex, these problems are very rare and can be prevented by seeds presorting.

These heat exchangers have a potential to recover heat from cooling cake and meal. In combination with preparation without flaking it would be possible to increase the energy gain by reusing the low-temperature heat to dry the seeds and warm up the seeds. The condition

to validate such a new processing is to complete the demonstration of the feasibility of pre-pressing without flaking warm and dry seeds as it has been done in the pilot plant of CREOL. Besides the energy saving of 38% mentioned, such an achievement would reduce odor emissions during cooking and reduce costs by eliminating the flaking and reducing the number of conveyors.

Conflicts of interests: The author has no interests in Solex thermal Science and this article is not sponsored by the said company.

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