Energetically optimized concentration of fruit juices

| Aroma recovery | Energy costs | Evaporators | MVR | TVR |

1 Introduction

Like all other industries, rising energy costs and demands to reduce primary energy consumption are current challenges facing the fruit juice industry. Even if prices for fossil fuels have fortunately been comparatively low in the last months, the medium and long-term trend is clearly characterized by a continuing increase. During processing of fruit to fruit-juice concentrate, evaporation is the process step with by far the highest energy requirements. Possible measures allowing a reduction in energy consumption of evaporator units to be achieved are therefore always monitored to ensure sustainable development of a company.

In order for investment in energy-saving evaporators to be profitable, the plant must be run with a sufficiently high number of operating hours per year. This requires a flexible plant design which allows processing of different types of fruit depending on their seasonal availability and providing plant capacity which can be adapted to suit the quantities of raw material available.

The following article presents evaporating concepts which satisfy the special requirements of fruit-juice concentrate manufacturing (preliminary and final evaporation, aroma recovery, high flexibility) with a very high degree of energy efficiency. In particular, it has been possible to meaningfully implement highly energetic efficient mechanical vapour recompression (MVR) technology for manufacture of fruit-juice concentrate.

2 Evaporation concepts in fruit-juice processing

During manufacture of fruit-juice concentrates, the juice constituents are concentrated for example from 12 to 70 % dry substance (brix) by removing the corresponding amount of water, in practically every case, by use of an evaporation system. As during the evaporation process, the valuable highly volatile aroma substances are also largely transferred into the vapour together with water, these need to be condensed to the greatest extent possible, concentrated in a suitable aroma unit and collected separately.

Use of alternative methods such as freeze concentration and reverse osmosis does not achieve the required end concentration and is therefore rarely seen.

2.1 Multiple-stage evaporation plants

On principle, a determined amount of energy is always needed to evaporate one kg of water at boiling point (2257 kJ/kg at 100 °C). This amount of energy is many times higher than that required to heat the liquid to boiling point. During condensation of water vapour, this energy is released again so that a further 1 kg of water can be vaporised with the condensating vapour as long as a sufficiently high difference in temperature is given to allow condensation to take place.

This principle is utilised in popularly used multiple-stage evaporation plants: Only the first stage is heated with boiler steam and part of the water removed from the juice. This vapour is then used in the second heating stage where it is condensed and used to remove a similar amount of water. In order to achieve the required difference in temperature for a heat transfer from the condensating vapour to the juice, this second stage must be carried out under a lower pressure and, therefore at a lower evaporation temperature. This principle can be repeated for several further stages. The possible number of stages is limited by the maximum allowable product temperature in the first stage and the required difference in temperature between the stages, whereby the increase in boiling temperature caused by the increasing sugar concentration must also be taken into consideration (approx. 6 °C at 70 brix).

In practice, 4 to 6-stage systems are most often used, sometimes 7 stages for a very large evaporation performance (fig. 1). The vapour from the last stage must be condensed in a condenser, usually cooled by cooling tower water, in order to maintain the vacuum. Without taking into account the amount of steam used for possible pre-heating of the product, the quantity of condensate corresponds approximately to the whole water evaporation divided by the number of stages. The size of the condenser and the cooling-tower performance should be designed correspondingly.

Fig. 2 shows the amount of steam consumed by plants with a varying number of process stages. The last stage is usually carried out at pressures of 100-150 mbar. The lowest attainable specific steam consumption for multiple-stage fruit-juice evaporators (7 stages) is around 0.18 kg/kg. Plants of this type are state-of-the-art and make a simple combination of preliminary and final concentration as well as aroma recovery possible in one plant.

Fig. 1: 6-stage and 7-stage evaporation plants for manufacture of apple-juice concentrate with a water evaporation rate of 25 or 50 t/h.

2.2 Plants with thermal vapour recompression (TVR)

A simple and cost-efficient possibility for improving energy efficiency is use of thermal steam jet compressors. Vapour is taken by suction into the steam jet compressor where it is mixed, e.g. in a ratio of 1:1.5 with live steam and heated further under higher pressure. The compressed vapour/steam mixture is then used to heat the same or an upstream process stage (fig. 3).

In this way energy savings corresponding to one or two additional evaporating stages can be achieved with a comparably low investment outlay.

This advantage is however, laid off against serious disadvantages:

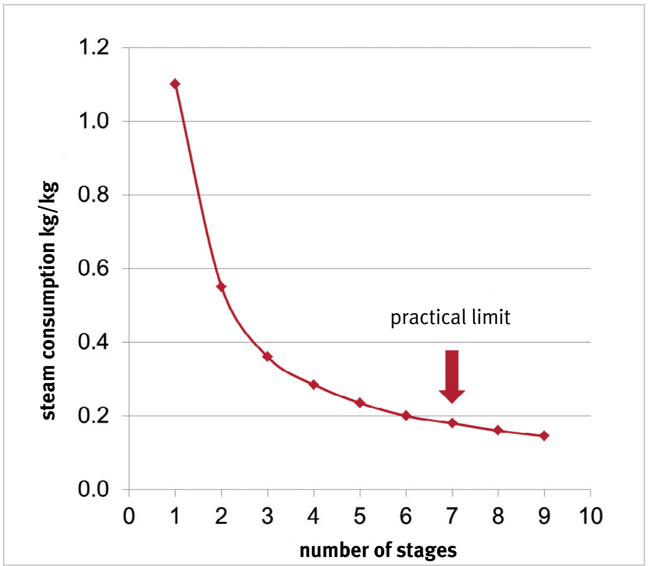

Fig. 2: Steam consumption in a multiple-stage evaporation plant

Mixing of live steam with vapour creates a condensate which can only be used in a production process utilising "culinary steam" e.g. for extraction of pomace or diafiltration. As a rule, it is also not possible to return the live steam condensate to the boiler and it needs to be replaced by (high cost) boiler feed water. In addition, if aroma recovery is intended during the evaporation process, special process control is required. Due to the functioning principle, steam jets can only be used in a narrow area around the design point. This limits the flexibility of use of the plant and running small quantities is only possible in a very limited way. Furthermore, steam jet compressors are very loud.

2.3 Plants with mechanical vapour recompression (MVR)

MVR involves compressing vapours to a higher pressure level with a mechanically driven compressor.

The working principle of mechanical vapour recompression can be explained using the Mollier diagram (fig. 4):

1. The saturated vapour is compressed by a mechanically driven compressor to create super-heated steam with a higher temperature and enthalpy.

2. Water (condensate) is injected in to the saturation point ➜ the steam is cooled down but still has a higher temperature and enthalpy than before compressing.

3. The compressed and saturated steam is projected onto the heating compartment of the evaporator body where

it is condensed and causes a similar amount of water to be evaporated from the juice in the product compartment. The vapour created is returned by suction into the mechanical compressor at the same temperature and enthalpy as the original vapour, closing the energetic circuit.

Mechanical vapour compressors are used in the fruit juice industry relatively seldom compared to other application areas such as the dairy or chemical industries. The reasons for this are the necessary division into preliminary and final evaporation, the often seasonal use of the plants and technical complications which arise from the recovery of valuable fruit aromas.

Fig. 3: Evaporation stage with TVR (thermal vapour recompression)

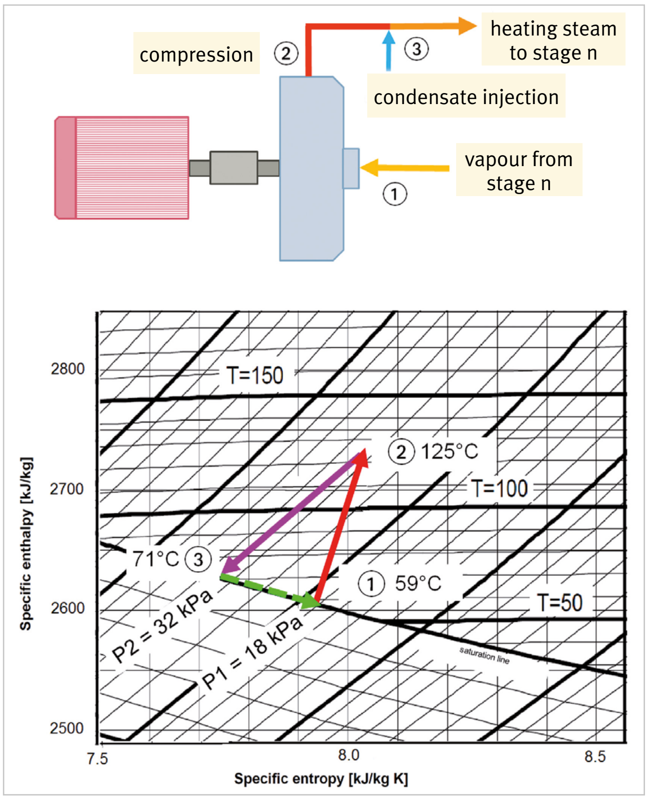

Fig. 4: Principle of mechanical vapour recompression (MVR)

The first MVR evaporators for fruit juice were introduced at the start of the 1980s with high-revolution turbo compressors (15000-20000 rpm). For the last 10-15 years, nearly all these applications have been carried out using direct-driven radial compressors (ventilators) (fig. 5) as these work very reliably, are less expensive to purchase, their maintenance is low cost, they are very energy efficient and simple to regulate.

Modern ventilator compressors have an energetic efficiency factor of 82 %. In a single stage process they achieve a temperature increase (dT) of maximum 8.5 °C which as a rule is not sufficient for final concentration. For this reason they are used today nearly exclusively for preliminary evaporation. Where higher temperature differences are required, two or three ventilator compressors can be used in series (table 1).

MVR plants have the lowest energy consumption and, therefore, the lowest running costs of all kinds of evaporators. The small difference in temperature between the heating steam and the product minimises negative effects on the product. Adjustment for operation with lower

Fig. 5: Ventilator compressor in an evaporation plant.

Table 1: Typical increases in steam temperatures using mechanical compression

Turbo-compressor	12 - 18 °C
1-stage ventilator	6 - 8,5 °C
2-stage ventilator	12 - 17 °C
3-stage ventilator	18 - 25 °C

quantities and concentrations can be carried out very easily by controlling the speed (rpm) of the motor.

One disadvantage of the MVR process is that delicate aroma substances can be partially destroyed by overheating of the steam during compression. This means that they must be removed beforehand, e.g. using a stripping column. Final concentrations higher than 60 brix require additional measures to achieve a sufficiently high difference in temperatures, e.g. a steam-heated final stage or use of a multiple-stage ventilator compressor. Finally, due to the low difference in temperature between the heating steam and the product, a relatively large heating surface is required.

3 Fruit-juice evaporation using MVR: Case studies

In the following, two case studies are described where MVR evaporators for different applications have been realised in recent years.

3.1 MVR preliminary evaporator with stripping column for aroma recovery

Fig. 6 shows the 3D image of an MVR evaporator for preliminary concentration of juice with an integrated aroma recovery system.

The plant uses a stripping column for aroma recovery. The slightly pre-concentrated juice without aroma is reduced to the required final concentration by passing three serial compartments of the main evaporator body, heated with MVR. The very small condenser emphasises the high energy efficiency of the plant as only here is a small amount of input energy lost.

This plant is very flexible: It can be run with 65-100 % of the nominal throughput, with/without degassing and with/without aroma recovery. It is designed for preliminary concentration of 36.4 t/h juice from 11 to 22 brix. 87 % of the evaporation is achieved in the MVR main stage where the ventilator compressor shows an energy consumption of approx. 300 kW. In addition, only 1.8 t/h steam is required to generate the stripping vapour and for aroma recovery. Table 2 shows a summary of the process and consumption data.

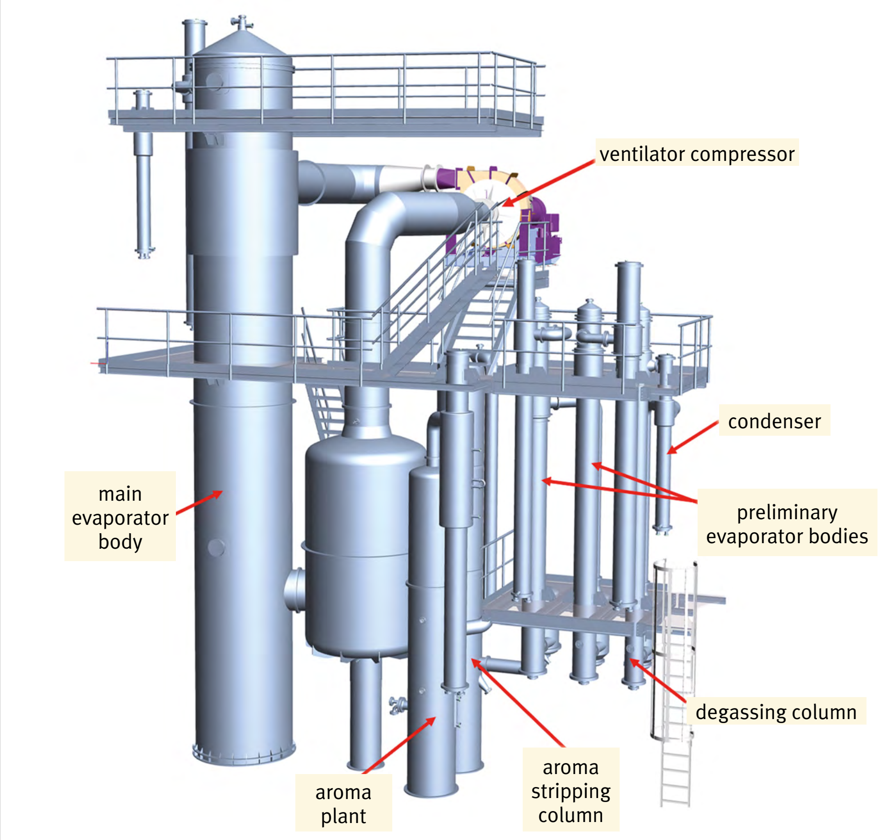

Fig. 6: Aroma recovery / preliminary concentration plant with a 1-stage ventilator compressor.

The whole installation is completed with a 6-stage final evaporator (separate plant) to achieve a final concentration of 70 brix.

3.2 Combined preliminary and final evaporation with MVR

The following case study describes a combined plant with preliminary and final evaporation which was later fitted with a multiple-stage MVR system.

The original plant was a combined system with 1-stage preliminary evaporation, stripping column for oil removal, aroma recovery, 3-stage final evaporation and thermal vapour recompression and was used for the concentration of citrus juice and extracts as well as apple juice. The customer was looking for a possibility of reducing energy consumption without limiting the flexibility of the plant.

This goal was achieved by installation of an additional evaporation stage and replacement of the TVR by three serially installed ventilator compressors. A 3-stage MVR was necessary to achieve the required difference in temperature between stages 1 and 3. As far as we know, this is the first juice evaporation plant to be used with a 3-stage MVR system.

Table 3 shows a comparison of the process and consumption data before and after conversion of the plant. Steam consumption for the whole 30 t/h water evaporation is reduced from 5.8 t/h to 1.7 t/h. Specific steam consumption was reduced from 0.193 kg/kg to a very low 0.057 kg/kg. In contrast, electricity consumption increased from 56 kW to 590 kW. The high energy efficiency can be seen in particular from the required cooling tower capacity reduced from 6700 MJ/h to 250 MJ/h.

Through this first-time use of a 3-stage ventilator, success was achieved in building a very flexible plant (different products, variable capacity, aroma recovery with/without stripping column), which makes it possible to utilise the very high energy efficiency of MVR technology throughout the whole concentration process (preliminary and final evaporation).

4 Cost effectiveness of MVR evaporators

Compared to the classic 5 or 6 stage evaporators, MVR evaporation systems require a 20-80 % higher investment.

Table 2: Process and consumption data – preliminary evaporator of the type AS 3502 / 180 Ve

Feed	36,4 t/h	11 Bx
Output	18,2 t/h	22 Bx
WE aroma stripping	2,4 t/h	1,2 t/h Stripping steam
WE ventilator stage	16,8 t/h	
Steam consumption	1,8 t/h	0,10 kg/kg
Electricity consumption	320 kW	
Cooling tower capacity	256 MJ/h	

Table 3: Process and consumption data, combi-evaporator before and after conversion

	before conversion	before conversion
WE (water evaporation)	30,0 t/h	30,0 t/h
Steam consumption	5,8 t/h	1,7 t/h
Specific steam consumption	0,193 kg/kg	0,057 kg/kg
Electricity consumption	56 kW	590 kW
Cooling tower capacity	6700 MJ/h	250 MJ/h

Table 4: Operating costs of the plant described in case study 2; running data as per Table 4

	before conversion	after conversion
Specific steam costs	30 EUR/t	30 EUR/t
Specific electricity costs	0,10 EUR/kWh	0,10 EUR/kWh
R (steam/electricity)	300	300
Operating hours	6000 h/year	6000 h/year
Steam costs	1.044.000 EUR/year	306.000 EUR/year
Electricity costs	33.600 EUR/year	354.000 EUR/year
Total steam + electricity	1.077.600 EUR/year	660.000 EUR/year
Savings		**-477.600 EUR/year**

In order for these higher capital investment costs to be profitable, they must be compensated by savings achieved in operational costs.

Operating costs of an evaporator are dependent to a great degree by the energy costs. Other variable costs (water, maintenance, personnel) are much less relevant and do not differ greatly between the different systems. The cost efficiency of MVR systems is largely determined by the reduction in overall energy consumption and a transfer from steam to electricity consumption. This means the cost ratio between these two forms of energy as well as the annual operating hours are decisive for cost efficiency of the MVR technology. The cost relationship "R" is defined as the ratio of the costs for 1 t steam divided by the cost of 1 kWh of electricity. In our experience, MVR technology becomes economically interesting when R is >250 and annual operating hours are >3000 h.

Table 4 shows a comparison of the operating costs of the plant described in case study 2 before and after conversion.

The energy cost ratio R for this customer was R = 300 and the plant was run with a very high number of operating hours, of 6000 h per year. With the operating data given in Table 4, this results in a reduction of steam costs from EUR 1,044,000 to EUR 306,000 and an increase in electricity costs from EUR 33,600 to EUR 354,000. In total, energy cost savings result to the amount of EUR 417,600 pro year.

Taking interest rates of 6 % on 50 % of the investment, the ROI for the conversion is achieved in only two years.

In this case, the short amortisation period is due to the very high running time of 6000 h per year. Acceptable amortisation periods for new plants can be achieved as a rule with a significantly lower number of operating hours per year, e.g. from 3000 h/year as the higher investment costs for a MVR evaporator compared to a conventional system are lower in relation to conversion of an existing plant.

5 Summary

Mechanical vapour recompression technology has the potential to significantly reduce energy consumption of fruit-juice evaporators. Meaningful use of this technology however, requires in-depth understanding of all qualitative and process requirements which an evaporator must fulfil when used in fruit-juice processing. In particular, utilisation of the high energy efficiency of MVR technology over the whole evaporation process (preliminary and final evaporation), in combination with recovery of high-quality aroma concentrates, requires sophisticated and innovative concepts.

The higher cost for investment in a MVR evaporator is offset by significantly lower energy costs. This higher investment is amortised more quickly, the higher the ratio of the specific steam to electricity costs and the annual operation time.

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