Energy Efficiency and Conservation Authority
Te Tari Tiaki Pūngao

Technical Information Document

MVR (Mechanical Vapour Recompression) Systems for Evaporation, Distillation and Drying

Technical Information Document 2019

New Zealand Government

Introduction

Mechanical vapour recompression (MVR) systems (also called MVR blowers) recover and reuse energy normally lost through evaporation. Because of the ability to use and upgrade wasted energy, MVR can significantly increase the efficiency of industrial heating and evaporation processes. They achieve this by recompressing vapour for reuse as a heat source for the same process from which the heat was recovered.

MVR technology is well established in New Zealand's dairy sector for the evaporation of milk. This is the most important example of high efficiency, open cycle heat pumps in New Zealand's process industries.

Traditionally, water removal from liquid milk prior to spray powder drying was achieved using multi-effect evaporators with five to six stages, or effects, to improve thermal efficiency. The heat input came from Low Pressure (LP) steam let down from cogeneration steam turbines, while input High Pressure (HP) steam usually came from coal-fuelled boilers. The dairy industry began using gas at a large scale in the late 1990's and at this point the HP steam was produced from steam generators heated by the waste heat from cogeneration gas turbines.

Thermal Vapour Recompression (TVR) steam ejectors were introduced to further improve the thermal efficiency of the evaporator train. In this system, Intermediate Pressure (IP) steam mixes with waste low pressure steam (under vacuum) from the evaporator in the TVR steam ejector. This TVR technology has also matured and is widely used at the finishing stage(s) in the milk evaporation process.

The breakthrough with MVR technology came with the use of steam compressors which elevate the pressure of the waste steam from the evaporator so that it can be re-used by condensing at a higher saturated temperature to drive the evaporation cycle. Many operational and process cost advantages were anticipated from this electro-technology including less residence time with improved product quality and lower wastage from cleaning as well as energy and GHG emission reductions[1]. Subsequently, MVR high-speed blowers have replaced the compressors and MVR evaporator technology has become the evaporator of choice for all new greenfield powder plants. There are over 100 MVR blowers on milk evaporators in the New Zealand dairy industry.

The New Zealand dairy industry has led the way with this energy efficient technology. However, other process industries have been much slower to apply the benefits of MVR technology. New advances in multi-staged arrangements and in small and higher speed MVR blowers are opening up new retrofit opportunities to continue to gain these energy efficiency benefits.

The focus of this technical note is on MVR technology for evaporation. There has been some progress in transferring MVR technology to drying, for example in superheated steam drying and heat recovery from waste steam applications. Multi-staging of MVR blowers also allows retrofit for distillation tasks which expands the opportunities for businesses to capitalise on New Zealand's renewable electricity resources.

1 The main operational advantage was the ability to use three MVR evaporators, with two on product and one being cleaned, so the large spray dryers could be run continuously for 30 days before a shutdown for cleaning.

Strata ENERGY CONSULTING

Efficient Energy International
Markets • Policies • Results

EECA commissioned Strata Energy Consulting and Efficient Energy International to produce this document which is one of a series on electrical heating.

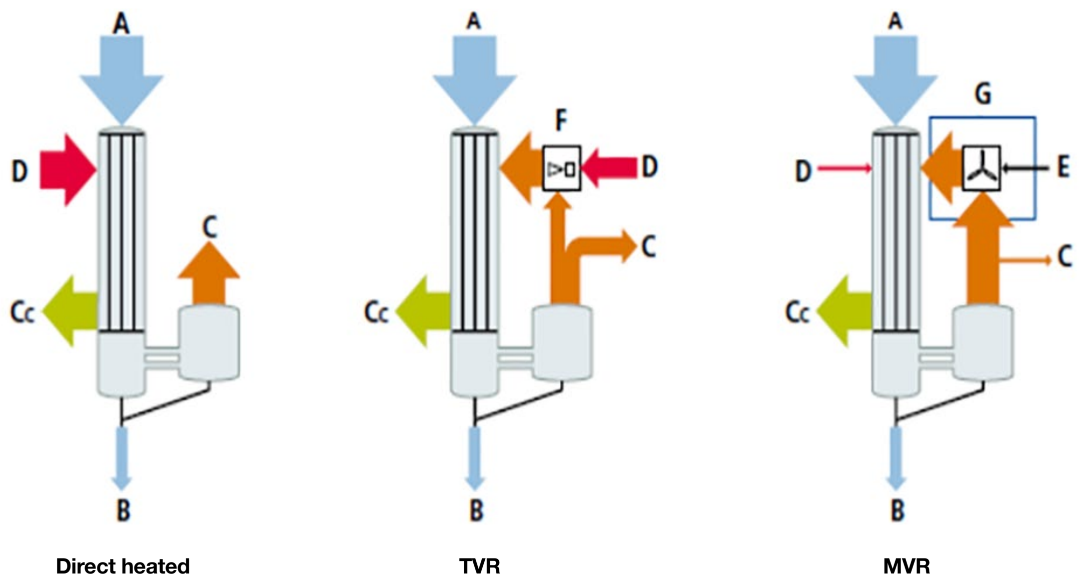
Technical features

Overview of evaporation processes

The three types of evaporators found in the New Zealand process industries are illustrated in Figure 2. The arrows in the diagram correspond to the magnitude of the mass flows, with red indicating input energy or steam into the system. The dilute process stream (A) is fed into tubes in the falling film evaporator. The concentrated stream (B) is separated from the evaporated vapour (C) which, for a dairy MVR evaporator, is steam under vacuum. The steam from the boiler (D) drives the heat transfer and the steam condensate (Cc) is removed[2]. In a direct heated evaporator, the vapour (C) normally feeds the next stage or effect (not shown for simplicity).

In a TVR system, part of the evaporated vapour is mixed with the feed steam (D) in the thermal ejector (F).

In a MVR system, the blower (G) raises the pressure and temperature of the evaporated vapour (C) to drive the heat transfer from in the evaporator. The steam (D) in the MVR evaporator is used as start-up energy.



Key:
A = Process stream, e.g. milk at 12% total solids
B = Concentrated stream, e.g. concentrated milk at >40% total solids
C = Evaporated vapour e.g. steam as water vapour from the milk
Cc = Condensate from the steam driving the heat transfer in the evaporator
D = Steam required from boiler – only used at start up
E = Electrical power to MVR blower
F = Thermo ejector for the TVR
G = MVR blower

Figure 1. The three different evaporation operations
Source: https://www.aireng.com.au/products/piller/

The MVR cycle described above can be considered to be an open cycle heat pump where the process fluid temperature is raised to provide the heat to drive the evaporator. It is an open cycle because steam from the mother liquor (milk in Figure 1) is used as the working fluid of the heat pump cycle. Modern MVR evaporators operate at very close temperature lifts, an increase of around 5°C allows them to deliver a very high Coefficient of Performance (COP), often close to 50.

Control is essential to MVR evaporation process efficiency. Varying the blower speed with an electronic variable speed drive provides for precise control over the pressure and temperature rise, and therefore over the rate of evaporation.

2 The steam condensate (Cc) from dairy industry TVR and MVR evaporators contains evaporated water from the feed process stream and this is known colloquially as cow water.

New high-performance MVR blowers have variable impeller speeds (up to 300 m/s) which can be optimised for the best possible aerodynamic loading and efficiency. Various shaft seals, new water injection nozzles and new instruments to control the speed accurately, are also available.

Demand for increased blower performance has grown and now most modern MVR blowers run well over their first critical speed. The optimal operating speed of many modern blowers is between 3,000 rpm and 3,600 rpm. At this high speed, the limitations of fluid film bearings will restrict the operating speed range.

To overcome the limitation of the bearing systems, one manufacturer has developed a new squeeze oil damper bearing system. This development allows the critical speed of the blower to be lowered well below the required operating range to provide maximum operating flexibility for the MVR unit.

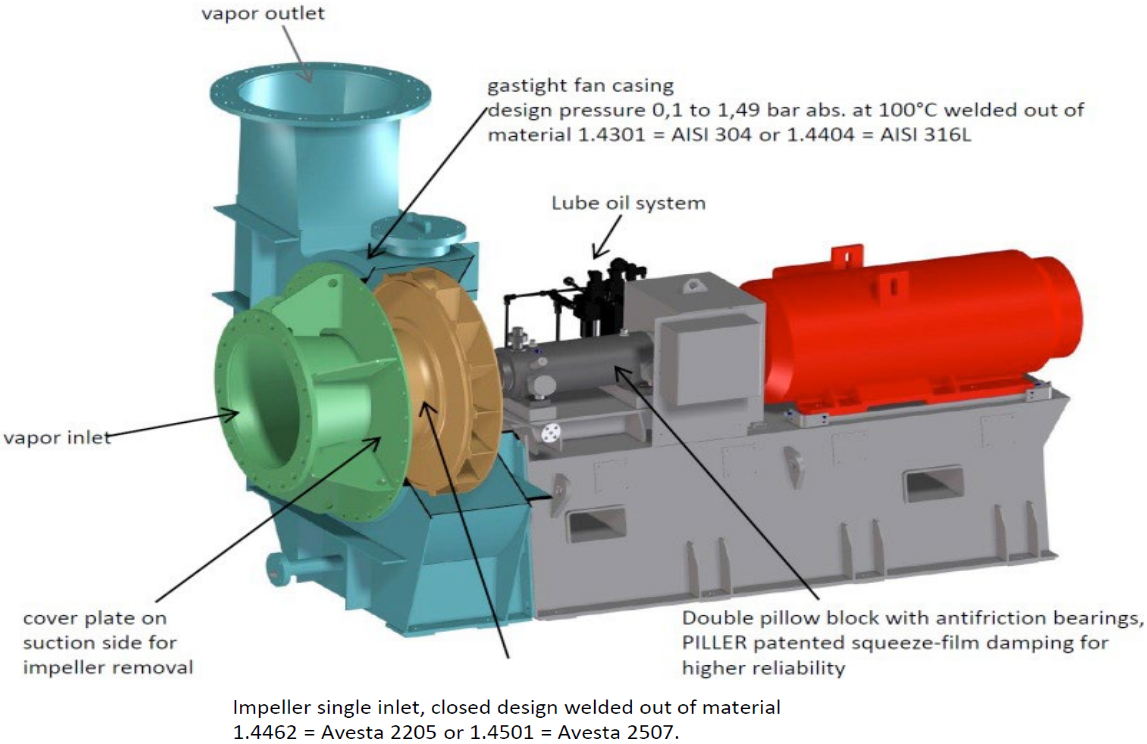


Figure 3. MVR blower
Source: Piller.de

Notes: This diagram is an example of MVR with a squeeze oil damper bearing from Piller.de in Germany.

Modern MVR systems

A typical MVR specification to compress steam includes motors up to 3 MW in size. The temperature increase for a single stage is usually up to 10°C, with tip speed up to 320 m/s and observed efficiencies of up to 86%. MVR blowers in the dairy industry are common in the 0.5 MW to 1.0 MW size range for large powder plants.

There are two developments in MVR technology which open new retrofit and greenfield applications:

1. multi-stage steam regeneration
2. high speed blowers for small MVR processes

Multi-stage MVR uses several MVR systems in series to increase the temperature lift for waste heat recovery. One manufacturer operates up to eight MVR blowers in series. This means that process operations such as distillation and drying processes, can now obtain benefits from MVR technology. Figure 3 shows four MVR blowers staged in series being used to provide a temperature lift of 40°C to drive a distillation column; manufacturers currently have used up to 8 MVR blowers in series.

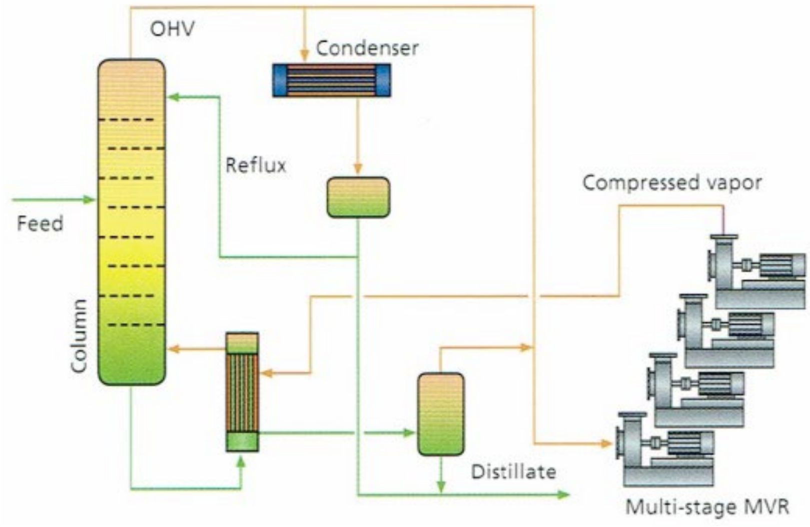


Figure 4. Multi-stage steam regeneration with MVR blowers for a distillation column
Source: Piller.de

The application for MVR in closing-up the drying stage in a process is more complex and relatively new. The waste air exhaust streams from dryers are air/steam mixtures often well below the dew point, and they can contain fine particles which can create problems in heat recovery. Considerable Research, Design and Development (RDD) work is occurring internationally on the development of closed loop drying systems especially for energy efficient milk powder production[3].

Early work has been completed using superheated steam drying in the New Zealand timber drying industry involving a small electrical compressor[4].

The mechanical pulp refining industry has explored MVR technology to upgrade waste steam from the refiners for use in pulp and/or paper drying. A case study at a Bowater mill has been well documented by EPRI[5]. In concept, a series of MVR blower(s) could be used to recycle waste heat back to the dryer.

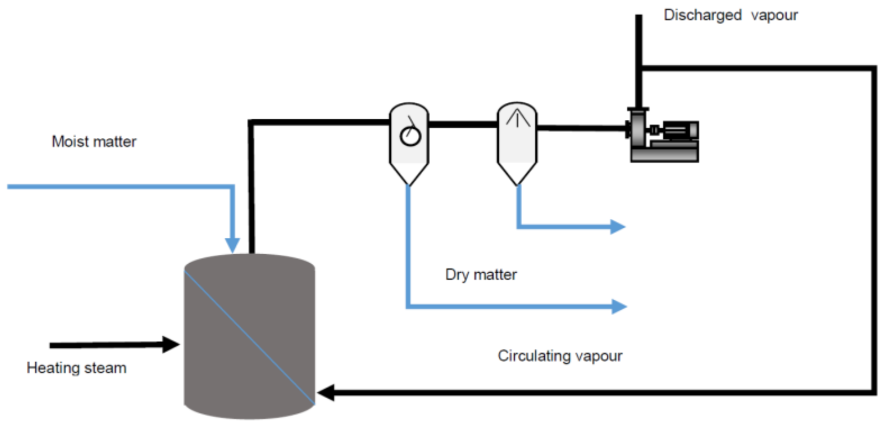


Figure 5. A simplified MVR loop for a MVR drying operation
Source: Piller.de

Further development involves small, high speed blowers up to 12,500 rpm for small steam flows around 1 t/h to 3t/h with 40 kW motors. These smaller MVR systems may be ideal for retrofitting the TVR finishing stage of an evaporator train.

Demonstration work is again required to de-risk this type of retrofit.

3 S N Moejes, et al, Closed-loop drying solutions for energy efficient powder production, Innovative Food Science and Emerging Technologies 47 (2018) 24-37, Elsevier
4 Researchers strive for quality drying, Market Matters, March 1996 pages 26-27
5 Heat pumps in pulp&paper processing, EPRI TechApplication Vol 3, No 6. 1991

Benefits

Lower specific energy consumption

Applying an MVR with a very high Coefficient of Performance (COP) substantially reduces primary energy use from burning fossil fuels and delivers large overall GHG emission reductions.

Higher energy efficiency

Recycling most of the waste heat using high performance blowers with low losses is a very efficient process. Also, operating MVR evaporators upstream of a large powder dryer to keep it running continuously is more energy efficient than shutting it down each day.

Greater flexibility

Accurate control of MVR blower speed can very precisely control the evaporation rate.

Higher product quality

A reduction in temperature degradation and a lower residence time for the product in the MVR evaporator has benefits of improved quality and less waste from cleaning.

Lower emissions

By running on electricity, MVR evaporators will reduce the on-site emissions of fossil fuel boilers.

Lower capital costs

The installation of MVR technology as part of greenfield site developments should lead to improved use of capital as there is less need for boiler or cogeneration capacity.

Challenges

Integration requires careful design

MVR blowers have to be integrated carefully into the process design in order to achieve lower costs overall. This optimisation is done using pinch technology. It is important that the MVR unit is across the process pinch (the basic rule for the integration of an industrial heat pump).

Electricity capacity requirements

In some circumstances, such as when replacing fossil fuel boilers, MVR units may require increased electricity capacity at the installation site, especially if a multi-staged design is required.

Manufacturers, suppliers and sources of further information

There is considerable experience using MVR technology in dairy industry applications in New Zealand. This MVR experience is yet to expand widely into other process heat applications.

New Zealand Suppliers

Windsor Engineering (Piller)
https://www.windsor.co.nz

Tetra-Pak
https://www.tetrapak.com

GEA Engineering
http://www.geap.co.nz

Global Suppliers

Howden Flakt Woods
https://www.flaktgroup.com/

Application Notes

In New Zealand, MVR has been used almost exclusively in the dairy industry. Applications have, however, grown globally in many different sectors:

Milk and whey	Citric Acid	Paper drying
Fruit juice	Sewage sludge	Saline water
Sugar	Liquid manure	Boiler feedwater
Yeast	Oil recycling	Blood plasma
Bioethanol	Seawater desalination	Electrolyte baths
Gelatine	Wood drying	Petrochemical industry

Table 1. International applications of MVR

Economic considerations

The costs of MVR evaporators are well known in the New Zealand dairy sector and its technology suppliers. The costs tend to be specific to individual applications and require detailed analysis of product and process conditions using process integration techniques.

Compared to more conventional direct-heated evaporators, MVR systems can require a higher investment with this being offset by the achievement of multiple benefits including flexibility in operation, energy efficiency and higher product quality.

Three factors key to MVR economic performance are:

a. The difference between the marginal cost of process steam and electricity.
b. Having a high plant utilisation rate in order to achieve an acceptable investment return. The dairy industry typically runs its large MVR evaporators for 6,000 hours annually.
c. Consideration of the future benefits of reducing GHG emissions and the future carbon price for this energy intensive operation.

Research undertaken by the University of Waikato's Energy Research Group has identified indicative costs for MVR blowers, these costs are provided in Figure 6.

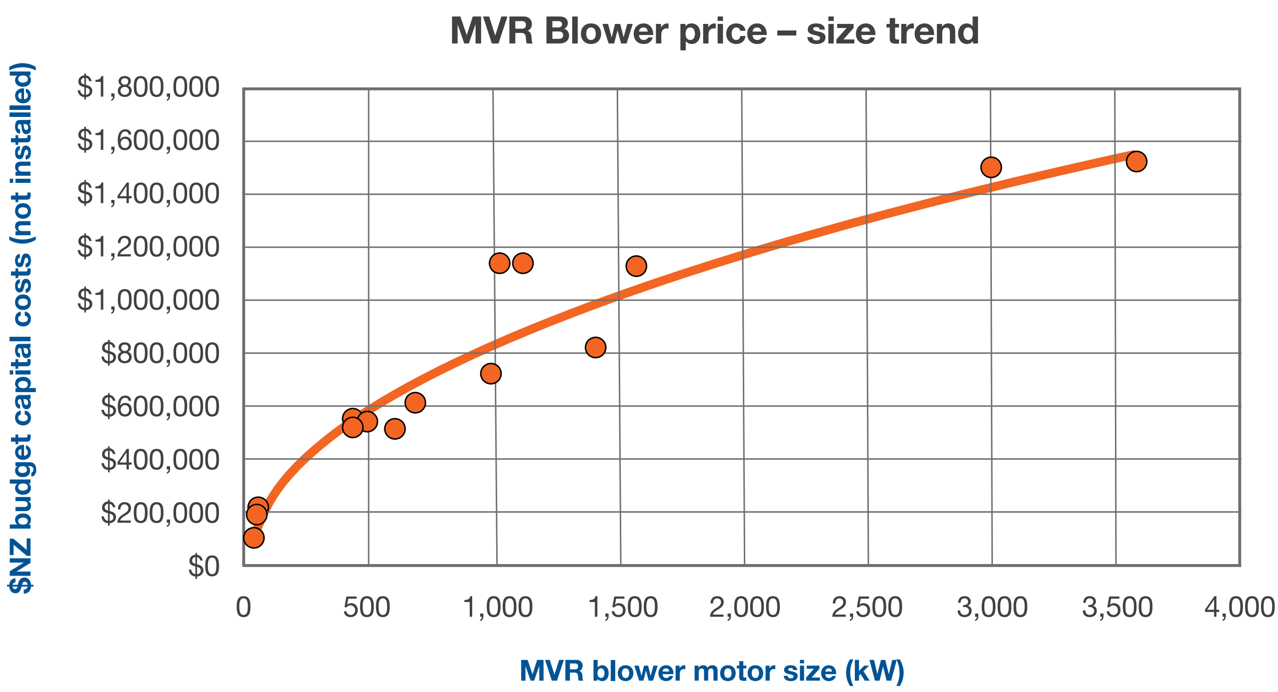


Figure 6. Capital costs for MVR blowers
Source: Atkins M J, The Energy Research Group, the University of Waikato

Common MVR applications

Dairy

MVR evaporation is well established for the large scale concentration of milk products in New Zealand. MVR evaporators at milk processing plants have been shown to significantly reduce energy input and reduce GHG emissions.[7]

Fruit Juice concentration processes

This application should suit MVR technology well. Fruit juice concentrates are produced by evaporating between 12% and 70% of water from fruit solids. During evaporation, volatile fruit aroma substances are also transferred into the vapour together with water. These need to be condensed and collected in a separate aroma unit. Freeze concentration and reverse osmosis are not able to achieve the required concentrations so MVR evaporation is an ideal process for fruit concentration. Typically, more than one evaporator stage is required for fruit juices as a single stage temperature increase is inadequate for the final concentration. This is explored in a case study below.

Other concentration and evaporation applications

MVR can be effectively implemented in a wide variety of processes where the separation of high volatility substances (water, alcohol etc.) is required; it can be used in brewing and alcohol distillation processes, in the concentration and extraction of starch, sugar, salts and other compounds, and in waste processing and in desalination.

Installation design

Improving the thermal efficiency in process heat systems requires a fundamental understanding of hot and cold streams and how the separators (evaporation, distillation and drying) can be integrated to minimise site-wide energy use of both hot and cold utility. This has been done for the last 30 years using pinch technology methods known as process integration.

Step 1

Establish an accurate picture of the process Heat and Materials (H&M) balance and where the evaporation requirements fit, and the impact of the process on the product quality needs.

Step 2

Determine the hot utility targets (process steam end-use demand) for evaporation across the total site (not just boiler fuel input or steam demand, but the target). Often, the integration of the preheating of the product feed streams and heat recovery of the cold water is crucial to site economics.

Step 3

Compare the electrical load profile needed by the MVR blower to the existing demand capacity and energy costs of the electricity supply. Understanding the power quality requirements of the MVR blower motor(s) is central to reliable production.

7. Case Study 1, describes the MVR at Anchor Products at Waitoa in 1996 where 5.8 GWh of electricity was replacing 49 GWh equivalent of coal in steam boilers. This paved the way for the expansion of MVR evaporators in the dairy industry over the last 20 years.

Estimating energy use and potential for CO_2 emissions reduction

Electric MVR will not directly produce any climate change gas emissions, but a proportion of the electricity used may have been generated from non-renewable sources that do produce climate change gases. In New Zealand, the proportion of non-renewable generation is low; any climate change gas impact from MVR operation will be much lower than for gas or other fossil fuel heating options.

To estimate how much CO_2 emissions will be reduced by adopting MVR the following rule of thumb comparison:

Electricity

CO_2 = kWh consumed x 0.1

For every 100 kWh of electricity used 10 kg of CO_2 is emitted

Gas

CO_2 = kWh consumed x 0.216

For every 100 kWh of gas used 21 kg of CO_2 is emitted

Note: In some industrial situations, electricity may be generated from co-generation of combined heat and power (CHP) situations. In these circumstances, the emission factor for electricity will be site specific.

Estimating energy use example

The potential electricity consumed by a 1,000 kW high temperature MVR unit, with a COP of 40, operating in a seasonal production environment at 24 hours a day, 7 days a week, for 20 weeks a year is:

1000 x 24 x 7 x 20 = 3,360,000 kWh or 3,360 MWh/year

Generally, an MVR unit will not need to operate at full output continuously and will automatically control its output to deliver the required heat or may be working alongside other MVR units. In this example, we will use a 70% load factor which means that the electricity used will be:

3,360 x 0.7 = 2,352 MWh

The amount of CO2 emitted by the generators producing the electricity is estimated by multiplying the MWh of electricity used by 0.1. This shows that 235 t/CO_2 per year will be emitted.

The energy output to the process for heating is calculated by multiplying the MWh input by the MVR COP:

2,352 x 40 = 94,080 MWh

For comparison, a gas TVR heating option with a COP of 5 operating at 70% load factor will use 18,816 MWh of gas. The amount of CO_2 emitted by burning the gas is calculated by multiplying the MWh by 0.216 = 4,064 t/CO_2.

So the gas TVR option will lead to 17 times more greenhouse gas emissions than the equivalent heat output MVR system.

In summary, electric high temperature MVR use significantly less energy than an equivalent gas TVR option and, because the electricity use for MVR emits significantly less greenhouse gas than the equivalent fossil fuel options, MVR can reduce your production CO_2 emissions.

Case studies

Case study: MVR helps cope with milk supply

This case study is reprinted from ECNZ (the Electricity Corporation of New Zealand), 1996. It describes how the Anchor Products new milk powder plant at Waitoa chose a composite MVR and TVR finisher evaporator system. This information was used at resource consent hearings to provide evidence that new electro-technologies would reduce GHG emissions through their higher efficiencies.

To cope with a rapidly increasing milk supply, three MVR evaporators were installed to feed a 12 t/h skim powder spray dryer. The unusual feature at this time was the use of three MVR evaporators to allow two to be used at any one time, while the third was cleaned. This ensured that the spray dryer could be run continuously for 30 days before it needed to be cleaned. This improvement in productivity has become the norm for the industry.

Table 2 shows a comparison of the total energy use between the new MVR evaporators and a standard TVR arrangement for the same evaporation duty. 5.8GWh of electricity has displaced 49 GWh of coal use due to the heat pump advantage of the MVR.

	MVR	TVR	Difference
Electricity GWh/y	7.3	1.5	5.8
Coal GWh/y	15	64	49
Total energy GWh/y	22.3	65.5	43.2

Table 2. Indicative MVR energy savings
Source: MVR helps cope with milk supply, ECNZ case study 3, Evaporation and Drying, Energy Services Technology Transfer.

Case study: Retrofitting a fruit concentration plant with preliminary and final evaporation with multiple-stage mechanical vapour recompression system

The original plant was a combined system with one-stage preliminary evaporation, stripping column for oil removal, aroma recovery, three-stage final evaporation and thermal vapour recompression. It was used for the concentration of citrus juice and extracts as well as apple juice. An additional evaporation stage and replacement of the thermal vapour re-compressor with three-stage mechanical vapour recompression achieved the required temperature increase between stages one and three.

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 0.057 kg/kg. At interest rates of 6 % on 50 % of the investment, the ROI for the conversion was achieved in two years.

	Before conversion	After conversion
Specific steam costs	30 EUR/t	30 EUR/t
Specific electricity costs	0,10 EUR/kWh	0,10 EUR/kWh
Steam/electricity cost ratio	300	300
Operating hours	6,000 h/year	6,000 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
Cost savings		-477,600 EUR/year

Table 3. Indicative fruit concentration MVR retrofit costs
Source: Energetically optimised concentration of fruit juices. Fruit Processing. Sept-Oct 2016.
http://www.bucherunipektin.com/sites/default/files/download_center/FP_Evaporator_EN_Sonderdruck.pdf

Case study: Mechanical Vapour Recompression versus Thermal Vapour Recompression. (California)

This case study highlights the choices and issues in installing either a thermal vapour recompression (steam ejector) evaporator or a mechanical vapour recompression evaporator.

The original design of the finisher assumed a 1,700 lb/h steam thermal vapour compressor as these are generally the lowest capital cost. At a cost of USD 8.11 to generate 1,000 lb of live steam, the operation of this evaporator would cost about USD 275 (in direct steam costs) per 20 hour run period. The client was not confident that the current boiler could spare the 1,700 lb/hrof steam for the finisher.

A mechanical vapour recompression finisher would need approximately 40 kW of electrical power to achieve the evaporation capacity. The local cost of electricity at USD 0.11/kWh would mean that this 40 kW turbofan would consume about USD 145 worth of electricity in a 20 hour production run, a yearly energy cost savings of about USD 29,000 at 4,000 hours per year production.

Capital costs are significant for a mechanical vapour recompression compressor. A thermal vapour recompressor steam ejector would cost roughly USD 15,000. The MVR compressor would cost almost USD 250,000. Taking the additional installation cost and increase of the finisher heating surface area into account, there was a 16 fold increase in capital costs for the compression technology. The MVR option would take almost 10 years to break even with the thermal vapour recompression option.

These case studies highlight the importance of steam consumption and cost in mechanical vapour recompression performance. Other points need to be considered:

- For the plant in California, the TVR option only needed two passes while the MVR option required the addition of a third pass in order to meet capacity.
- MVR evaporators still require some steam because they generally run close to their limit on vapour availability for evaporating product, so it is necessary to introduce steam to stabilise the system. This particular evaporator was assumed to require about 625 lbs. of steam for starting up and about 200 lbs/h of steam for balancing during a 20 hour run.
- Even with the addition of a small boiler to provide the steam required by the TVR, it would still take the MVR around 10 years to break even.

Source: Evaluation of a MVR versus TVR heated falling film finisher.
GLM Hydro. 2015

http://www.glmhydro.com/other/evaluation-a-mvr-versus-tvr-heated-falling-film-finisher/

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