MESSO-CHEMIETECHNIK

Steam Jet Refrigeration Plants and their Range of Application

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Reprinted from BRITISH CHEMICAL ENGINEERING, March 1969

Many processing operations require refrigeration and there are several ways of producing the cold. Below the author discusses the simple technique of steam jet refrigeration, and its use range; he compares its economy with that of vapour compression so as to show where steam-jet refrigeration is to be preferred.

by W. WÖHLK*

Steam jet refrigeration plants and their range of application

Mode of operation

THE cooling of water or any solution is effected in steam-jet refrigerating plants by evaporating a part of the water or solution under vacuum. For example, if water enters an evacuated chamber – the evaporator – where the pressure is lower than the saturated steam pressure, which is proportional to the water temperature, a part of the water evaporates.

This evaporation produces a chilling of the water. The evaporation process is continued until a temperature is reached at which the saturated steam pressure corresponds to the pressure in the evaporator. The resultant vapours are condensed in an after-condenser.

The vacuum required for evaporation is maintained by a vacuum pump connected to the condenser. If water is used as a means of condensation, the temperature of the water leaving the evaporator can only be as low as the temperature of the water leaving the condenser. But when inserting a compressor between the evaporator and condenser, the water can be cooled down further to a temperature which is considerably lower than the cooling water discharge temperature. The compressor then compresses the steam produced from the lower pressure in the evaporator to the higher pressure in the condenser.

At low pressures, which are necessary for the cooling process, steam has a large specific volume which would require mechanical compressors of large dimensions. Here, the steam-jet vapour compressor has proved to be most suitable [1]. Besides its relatively small dimensions, even when conveying big steam volumes, the steam-jet vapour compressor has the advantages of simple operation and no movable parts so that a long and trouble-free life is ensured with minimum maintenance.

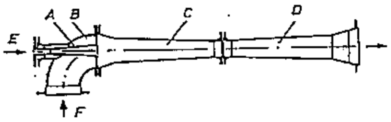

Fig. 1 Steam-jet vapour compressor. *A*, forcing nozzle. *B*, ejector head. *C*, mixing nozzle. *D*, pressure nozzle. *E*, operating steam. *F*, suction steam.

Figure 1 shows such a steam-jet vapour compressor. The operating steam enters at connection (e) and leaves the nozzle at (a) where it expands to a pressure which is just under the required suction pressure. This pressure drop produces a higher velocity of the operating steam up to about 1,000 metres/sec. The vapours are drawn in by the turbulence forming at the outlet.

In the mixing nozzle (c) the operating steam is mixed with the induced vapours at a constant pressure. The pressure is then increased to the necessary level in the pressure nozzle (d).

A further advantage of the steam-jet vapour compressor is that the operating steam can be condensed together with the vapours drawn in.

When discussing the simple construction of the steam-jet vapour compressor, the rather complicated processes that take place in it should not be overlooked.

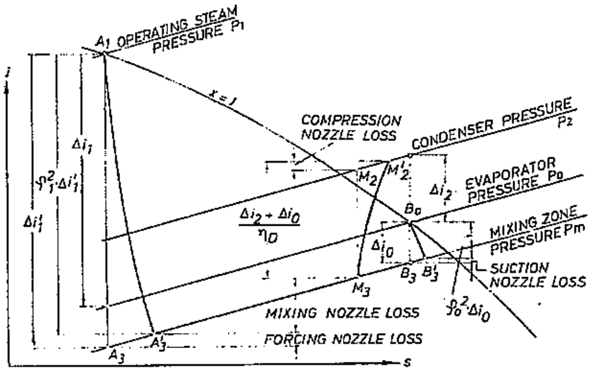

Fig. 2 i-s diagram showing the processes in the steam ejector.

In particular, the losses cannot be calculated exactly. Figure 2 represents an i – s diagram illustrating the processes in a steam-jet vapour compressor.

In the case of an adiabatic operation the operating steam would expand from point A_1 to point A_3. Owing to the efficiency of the forcing nozzle ϕ_1^2, however, point A'_3 is reached. Thus, the transformation of energy per kg of operating steam is $\phi_1^2 \,.\, \Delta_{i_1}'$. The decrease in the enthalpy entails an increase in the velocity of the operating steam.

The energy content of the vapours drawn in is $\phi_0^2 \,.\, \Delta_{i_0}$. This energy is liberated between points B_0 and B'_3. In the mixing nozzle (c) the operating steam and induced vapours are mixed at a constant pressure p_m. At the end of the mixing process, point M_3 is reached. From this point the mixture is compressed in the pressure nozzle (d) to the pressure in the condenser p_2 by means of an enlarged cross section. Finally, the compression point M'_2 is attained.

It can be seen from the energy equation [2] for steam-jet vapour compressors that the specific steam consumption, μ, which is the operating steam volume that is required for the compression of 1 kg of induced vapours, is essentially a function of the ratio between the compression energy Δ_{i_2} and the expansion energy Δ_{i_1}.

Figure 3 shows practical data from tests [1]. They correspond to the calculated figures.

The total efficiency, η, of steam-jet vapour compressors is defined as the ratio between the compression energy Δ_{i_2} and the expansion energy $(\Delta_{i_1} - \Delta_{i_2}) \,.\, \mu$.

Corresponding transformations on the basis of the energy equation result in the efficiency η as a function of the specific operating steam consumption μ. This function is shown by the graph of Fig. 4.

Since the development of the steam-jet vapour compressor is now basically completed, the ejectors made by different firms have all approximately the same optimum efficiency.

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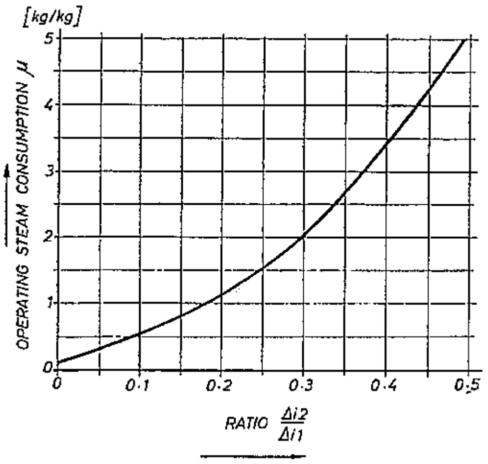


Fig. 3 Practical data for the specific forcing steam consumption of steam-jet vapour compressors.

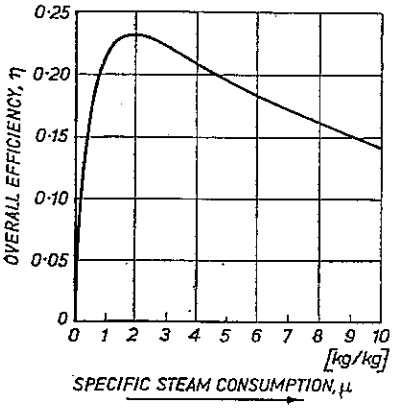


Fig. 4 Curve showing the efficiency of ejectors.

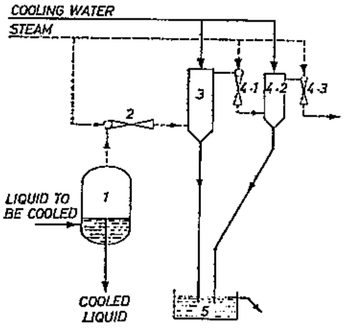


Fig. 5 Scheme of a single-stage steam-jet refrigerating plant. 1, evaporator. 2, steam-jet vapour compressor. 3, main condenser. 4, two-stage steam-jet vacuum pump. 4.1, steam-ejector for evacuating the main condenser. 4.2, intermediate condenser. 4.3, steam ejector for evacuating the intermediate condenser. 5, cooling water collecting tank.

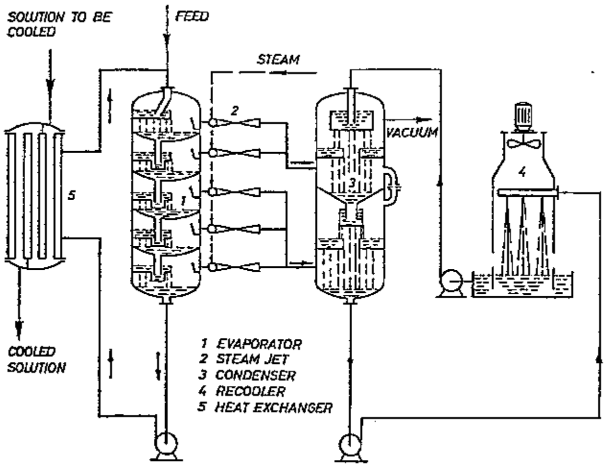
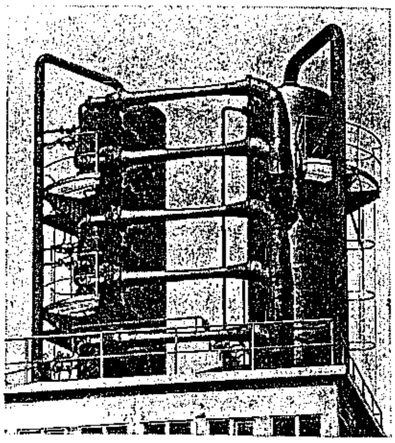


Fig. 6 Five-stage steam-jet refrigerating plant.

Fig. 7 Five-stage steam-jet refrigerating plant set up outdoors, with a capacity of 1,000,000 k.cal/hr, for cooling 100 m³/hr cold water from 20 to 10°C. Mean cooling water temperature. Maximum cooling water temperature 30°C. Cooling water consumption 290 m³/hr at a cooling water feed temperature of 20°C. Steam consumption 2,600 kg/hr at a waste steam pressure of 1 atm.g.



According to Fig. 4, the maximum total efficiency of a vapour compressor is about 23%. This maximum efficiency is attained at a specific operating steam consumption of about 2 kg/kg.

The efficiency of mechanical compressors is considerably higher than that of steam ejectors. Nevertheless, steam ejectors are more economic, in particular when using cheap waste steam.

Steam-jet refrigerating plants require steam and cooling water as energy.

Figure 5 shows the arrangement of a single-stage steam-jet refrigerating plant. The heated water from the cold-water circuit expands into the evaporator [1] and cools down by the evaporation of a part of the water. The cooled water is pumped from the evaporator and returned to the cold-water circuit. The vapour compressor [2] conveys the vapours produced during evaporation into the main condenser [3] where they are condensed, together with the operating steam of the vapour compressor, by means of the cooling water. The steam-jet vacuum pump [4] discharges the inert gases into the atmosphere and thus maintains the required vacuum in the main condenser.

Types of plant

Besides the design consisting of one vertical evaporator and one direct-contact condenser, there are various other types of construction.

In order to save steam and cooling water, the cooling and condensation can be carried out in several stages.

The scheme (Fig. 6) represents a steam-jet refrigerating plant with a five-stage evaporator.

If the available cooling water is limited, the cooling water from the condenser will – as shown in Fig. 6 – be circulated via a vaporisation recooler where the warmed water is chilled by evaporation. This means that only the evaporated water will have to be replaced by fresh water.

Because of its surface-free operation, the direct-contact condensation is preferred when there is no need to recover the live steam condensate. Direct-contact condensers should be used in any case for dirty cooling water.

Surface condensation is applied when volatile matters are given off by the solution in the evaporator, or when the live steam condensate has to be recovered.

Figure 7 illustrates a steam-jet refrigerating plant with one surface condenser. The liquid is cooled in a two-stage horizontal evaporator. The plant has a refrigerating capacity of 25,000 k.cal/hr. The whole unit is mounted on a common base frame.

The arrangement of every steam-jet refrigerating plant can be adapted to the conditions existing at the site of erection.

Figure 8 shows a steam-jet refrigerating plant with a capacity of 1,000,000 k.cal/hr.

The evaporator is a five-stage horizontal type of construction. The condensation is effected in a two-stage vertical direct-contact condenser. This plant is sited on the roof of a building and requires only limited floor space.

As can be seen, it is possible to build plants of great height and small floor area, i.e. with vertical evaporators and vertical condenser – as shown in Fig. 8 – and alternatively of limited height and large floor area.

The steam-jet refrigerating plant shown in Fig. 9 is part of an air-conditioning plant, installed in a theatre. It has also a capacity of 1,000,000 k.cal/hr. The three-stage evaporator is of horizontal design to permit erection of the refrigerating plant in the theatre cellar. The limited headroom necessitates a larger floor area.

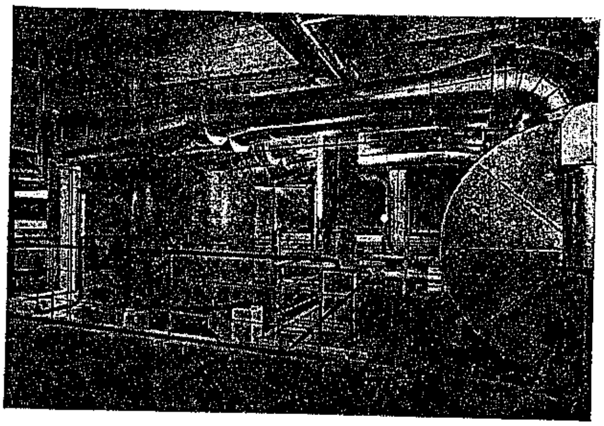


Fig. 8 Three-stage steam-jet refrigerating plant set up in the cellar of a theatre for the air-conditioning of the various rooms. Capacity 960,000 k.cal/hr. Cold water throughput 120 m³/hr. Cold water discharge temperature 14°C. Cold water feed temperature 6°C. Steam consumption 3,200 kg/hr. Steam pressure 3·5 atm.g. Cooling water feed temperature 25°C.

Control of steam-jet refrigerating plants

Steam-jet refrigerating plants can be adapted to any desired mode of operation. Since they are very straightforward plants, they can be operated manually.

Plants required to operate without significant load fluctuations do not require control and operating personnel. Failures of the steam, water, and current supply are the only breakdowns likely to interfere with the plant operation. Such failures can be indicated by acoustic warning signals.

If a steam-jet refrigerating plant with varying loads is to be operated without personnel, a semi-automatic control system will be advisable. The plant is switched on and off manually while all other operations are controlled automatically.

Figure 10 shows a five-stage semi-automatic steam-jet refrigerating plant. When the required refrigerating capacity decreases during the operation, the temperature of the cold water leaving the last evaporator stage would also become lower, provided the operation of the refrigerating plant remains unchanged. Now, the pressure in the last evaporator stage is regulated, and therefore the cold water discharge temperature also. If this temperature drops below a certain level, as many vapour compressors as is necessary are shut off, starting with the first stage, to achieve the proper cold water discharge temperature.

When the refrigerating capacity increases again, the pressure in the last evaporator stage becomes higher. If the actual value is higher than the rated value, the control device will restart the vapour compressors, commencing with the last stage.

When stopping some vapour compressors the steam volume to be condensed becomes smaller, and the condenser operation would no longer be economic at a constant cooling water volume.

The constant pressure maintained by a control device in the main condenser under varying loads, and in conjunction with an adjustable cooling water valve, has the effect that no more cooling water than is necessary enters the condenser. The shut-down of some vapour compressors entails a reduction in the cooling water flow, and the re-start an increase in the cooling water feed.

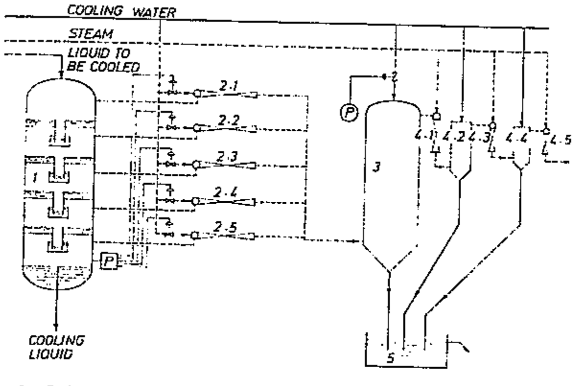


Fig. 9 Scheme of a five-stage steam-jet refrigerating plant (with control device). 1, five-stage evaporator. 2, steam-jet vapour compressor. 3, main condenser. 4, three-stage steam-jet vacuum pump. 4.1, steam ejector for evacuating the main condenser. 4.2, first intermediate condenser. 4.3, steam-ejector for evacuating the first intermediate condenser. 4.4, second intermediate condenser. 4.5, steam ejector for evacuating the second intermediate condenser. 5, cooling water collecting tank.

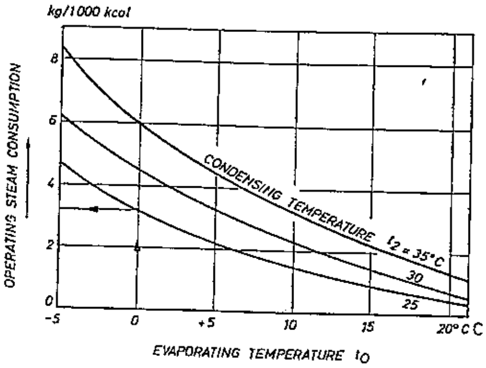


Fig. 10 Specific operating steam consumption of steam-jet vapour compressors at a steam pressure of 5 atm.g.

Generally, when using steam-jet refrigerating plants in air-conditioning units, a fully automatic operation is required, i.e. the start and shutdown of the complete plant is effected automatically in conjunction with a remote thermostat coupled to the air-conditioning unit.

Energy consumptions

The steam and cooling water consumption is of interest when applied to steam-jet refrigerating plants. There are publications [3] from which the steam consumption of a vapour compressor can be calculated (*vide* also Fig. 3).

The graph of Fig. 11 shows the operating steam consumption of a vapour compressor employed in a steam-jet refrigerating plant where the forcing steam pressure is 5 atm abs. The curve representing the live steam volume required for a refrigerating capacity of 1,000 k.cal is above the curve of the final cooling water temperature. The condensation temperature was chosen as parameter.

Based on this graph, the specific operating steam consumption ranges at 3·5 kg per 1,000 k.cal with cooling water down to 0°C at a pre-determined condensation temperature of 25°C.

If, for example, 10 m³ of water are to be chilled from 20°C to 0°C per hour, a refrigerating capacity of 2,000,000 k.cal/hr will be required resulting in a total steam consumption of 700 kg/hr.

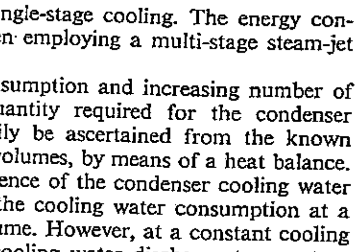


Fig. 11 Decrease of the steam consumption of a steam-jet refrigerating plant in dependence on the number of stages.

This example applies to single-stage cooling. The energy consumption is much lower when employing a multi-stage steam-jet refrigerating plant.

With decreasing steam consumption and increasing number of stages the cooling water quantity required for the condenser becomes smaller. It can easily be ascertained from the known vapour and operating steam volumes, by means of a heat balance.

A larger temperature difference of the condenser cooling water would entail a reduction of the cooling water consumption at a constant operating steam volume. However, at a constant cooling water feed temperature the cooling water discharge temperature rises with increasing temperature difference, i.e. the counter-pressure for the vapour compressor becomes higher. When compressing the vapours to a larger counter-pressure, more operating steam will be necessary for the vapour compressor, which would mean an increased cooling water consumption.

Optimum figures according to number of stages and condensation temperature result in minimum overall cost, consisting of price of plant and cost for steam, cooling water, and current. These figures can only be found by means of an approximate calculation.

Steam and cooling water cannot only be saved by cooling in several evaporator stages, but also by using a multi-stage condenser. In the case of a single-stage condenser all vapour compressors have to compress the vapours to a constant coun-

TABLE I—Cost comparison between a steam-jet refrigerating plant and a compression refrigerating plant

	Three-stage steam-jet refrigerating plant with direct contact condenser, fully automatic			Compression refrigerating machine with two compressors and vaporisation condenser		
(1) Investment cost plus energy feed and discharge	£9,400			£20,000		
(2) Annual capital yield						
(2.1) Interest and amortisation (9% per annum)			£850			£1,790
(2.2) Maintenance			£470			£1,980
Total capital requirement			£1,320			£3,770
(3) Energy cost per hour						
(3.1) Current (0·85d./kWh)	50 kW/hr	3·57/-d. per hour		245 kW/hr	17/6d. per hour	
(3.2) Cooling water (6d./m³)	only pumping cost included in 3.1			5 m³/hr	2/6d. per hour	
(3.3) Steam (9·8/-/ton)	2 to/hr	19/9d./hr		—		
Total energy cost		23/3d./hr			£1/hr	
(4.1) Annual energy cost (650 hours/year)			£750			£650
(5.1) Annual total cost			£2,075			£4,420
(4.2) Annual energy cost			£9,300			£8,000
(5.2) Annual total cost			£10,600			£11,950

ter pressure in the condenser, the pressure corresponding to the cooling water discharge temperature.

If the cooling water is warmed in two stages, the pressure in the second condenser stage is at a level corresponding to that produced by all vapour compressors using a single-stage condenser. The pressure in the first condenser stage is then lower. This means that the vapour compressors producing the lower pressure in the first condenser stages consume less operating steam.

Economics

In order to ascertain the plant best suited for a particular duty one has to compare compression, absorption, and steam-jet refrigerating plants with regard to their overall cost. Unfortunately, it is impossible to state in general terms when one or other type of refrigerating plant will be more economic.

Table I is a cost comparison between a steam-jet refrigerating plant and a compression refrigerating plant, referring to a particular case.

For the air-conditioning of an office block a refrigerating plant was installed in the cellar. The circulating water was cooled down from +14°C to +6°C, and the total refrigerating capacity 480,000 k.cal/hr.

A comparison of the investment cost provides a clear advantage of the steam-jet refrigerating plant over the compression refrigerating plant. The annual interest and amortisation cost are only half as high as for the compression refrigerating plant. Another favourable fact is that, owing to its simple structural arrangement and the absence of movable parts, it requires very little maintenance. Consequently, 5% maintenance costs have been stipulated for the steam-jet refrigerating plant and 10% for the compression refrigerating plant (in accordance with directives for apparatus and machines).

Thus the total capital requirement for the compression refrigerating plant is three times higher than for the steam-jet refrigerating plant. A comparison of the energy cost, however, shows an advantage of the compression refrigerating plant. The total energy cost of the steam-jet refrigerating plant is approximately 16% higher than that of the compression refrigerating plant. But when considering an operating period of 650 hours/year as basis, it can be seen that the total cost for the steam-jet refrigerating plant are less than half that of the compression refrigerating plant. For reasons of comparison, the total cost in case of a continuous operation over 8,000 hours/year have been calculated. Also in this instance, the steam-jet refrigerating plant is less expensive than the compression refrigerating plant, but its advantage is only marginal.

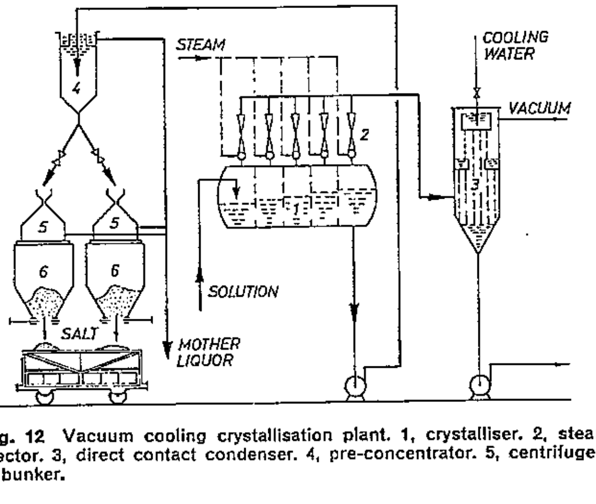


Fig. 12 Vacuum cooling crystallisation plant. 1, crystalliser. 2, steam ejector. 3, direct contact condenser. 4, pre-concentrator. 5, centrifuges. 6, bunker.

Summarising, it can be stated that a steam-jet refrigerating plant will be considerably more economic in cases where cheap low-pressure waste steam from turbines or any other process can be utilised and sufficient cooling water, e.g. from a river, is available so that only the cost for pumping has to be taken into account. When the plant is not to be operated continuously throughout the year, the low capital yield is a decisive factor for the profitability of a steam-jet refrigerating plant. In the case of a continuous operation over the whole year the limit of profitability would be at a final cooling temperature of about +6°C under normal conditions. But when it is used over shorter periods during the year, the steam-jet refrigerating plant can work more economically than other plants up to a final cooling temperature of −5°C.

Range of application

It has been demonstrated that steam-jet refrigerating plants will – when they are only used for the chilling of water or as part of an air-conditioning plant – reach a stage where they no longer have advantages over other types of plant in economic respect. If, however, the solution of technical process problems is concerned, the steam-jet refrigerating plant again becomes of the utmost interest. Processes requiring low temperatures and vacuum offer the steam-jet refrigerating plant wide fields of application; e.g. in the production of mineral water, the well-water has to have undesirable gases removed and be cooled down to a temperature at which the water provides good solubility for the carbon dioxide to be added. The production of vacuum merely for the cooling of the water is only a means to an end; it is of greatest importance for the removal of undesirable gases.

Indeed, in such cases the range of application in which the steam-jet refrigerating plant is economic can be considerably extended, even when operating it continuously throughout the year. However, there are many duties in the field of process technique for which steam-jet refrigerating plants are employed although they are less efficient than other types of refrigerating plants. One typical example is cooling crystallisation. Solutions whose saturation point for a dissolved salt decreases with reducing temperature were formerly cooled down by compression or absorption refrigerating plants to temperatures at which the required salt crystallised out. The refrigerating machine was then an independent unit providing the cooling medium only for the crystallisation plant. The crystallisation was mostly carried out in troughs, vertical containers or drums, equipped with cooling coils or jackets, in which the heat exchange between solution and cooling agent took place. The disadvantages of such a plant are obvious. In order to avoid excessive cooling surface areas the cooling medium has to be cooled down to a temperature far lower than the required solution temperature. Owing to the low coefficient of heat transfer when cooling a solution by means of a cooling medium, the heat exchange surfaces inevitably become very large. If aggressive solutions are to be treated, the crystalliser will have to be made of stainless steel so that the cost of plant becomes very high.

However, greater disadvantages occur during the operation of such a plant, for the salt crystallises out preferentially at the cooling interface, thus permanently increasing the resistance to heat transfer. This demands frequent cleaning of the cooling surfaces.

All these disadvantages are overcome when employing a steam-jet refrigerating plant for vacuum crystallisation. In recent years, plants of this type having the largest capacities have been used in continuous operation. Hourly outputs of more than 20 tons are no longer rare. In the past few years, Standard-Messo Duisburg has been erecting vacuum cooling crystallisation plants with a refrigerating capacity of more than 50 million k.cal/hr in total.

As already described at the beginning, the heat is extracted in the steam-jet refrigerating plant by expansion of the solution. Thus, no heat exchange surfaces are necessary on the cooling side so that rubber-lined apparatus can be used even when aggressive solutions are treated. On the condensation side either direct-contact condensers or surface condensers can be used. The most important advantages are, however, the simple construction, easy operation, and minimum maintenance. Figure 13 shows a five-stage cooling crystallisation plant.

The warm saturated salt solution expands into the crystalliser [1]. The vapours arising during the evaporation of part of the water are conveyed by the vapour compressors [2] into the main condenser [3].

The salt crystallised out during the cooling process is pumped together with the cooled solution from the last crystalliser stage into the pre-concentrator [4]. Salt-free mother liquor leaves the pre-concentrator from the top. The thickened salt slurry is fed from the top of the pre-concentrator to the centrifuge [5] in which the salt is separated from the mother liquor.

Figure 14 shows a part of such a cooling crystallisation plant. The warmed salt solution enters the first stage of the crystalliser [1] via the solution feed pipe. The vapour pipe [2] connects the first crystalliser stage directly with the second stage of the direct contact condenser [4]. The second stage and the vapour compressor [3] of the other crystalliser stages are linked up with the first condenser stage.

Up to the present, the concentration of fruit juices has mostly been carried out in thin-film evaporators, since, in order to avoid destruction of the vitamins during evaporation, the resident times at the heating surfaces must be kept as short as possible. The concentration can, however, also be effected without the addition of heat, if one succeeds in removing water by another method, e.g. the freezing method. When chilling fruit juice below its freezing point pure water crystallises out in the form of ice. For this purpose also, the steam-jet refrigerating plant finds another suitable field of application. The solution is cooled down by expansion into a vacuum chamber. The ice crystals can be separated from the concentrated fruit juice in a centrifuge. With this process the residence time is no longer of importance, since the solution is concentrated at very low temperatures and without external heat. This means that the use of a thin-film evaporator is not necessary. When evaporating fruit juices under the influence of heat the plant has to be followed by an aroma recovering equipment, which can be dispensed with when applying the freezing process, because at higher temperatures a proportion of the aroma also evaporates and is entrained with the vapours leaving the plant. If the evaporation of the fruit juice were carried out at temperatures at which the aroma is no longer volatile – i.e. at 20°C – it is not possible to use a multi-stage plant. A single-stage plant would, however, require about 586 k.cal, to be taken from the live steam, for the evaporation of 1 kg of water, whereas with the freezing method only 80 k.cal are necessary for the formation of 1 kg of ice. This amount of heat is increased by the amount required for cooling the fruit juice to the freezing temperature.

The construction and individual components of such a plant for the concentration of fruit juice can be compared with those of a vacuum cooling crystallisation plant. In the first plant the desired product is crystallised salt, in the second plant concentrated solution.

Today, the freezing method is also applied for the recovery of potable water from sea water (Fig. 15).

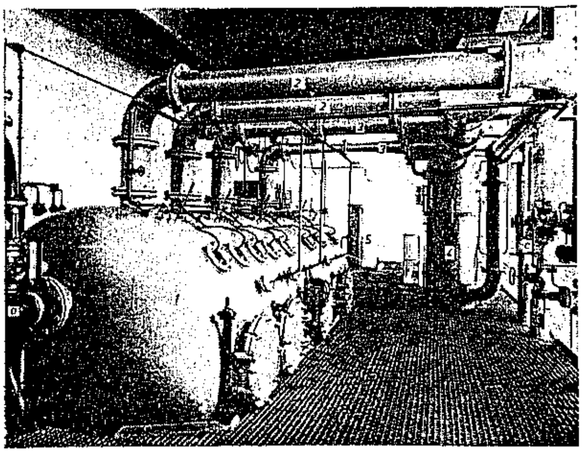


Fig. 13 Vacuum cooling crystallisation plant. (a) solution feed. (b) cooling water distribution. (c) steam distribution. 1, crystalliser. 2, vapour pipes. 3, steam ejector. 4, two-stage condenser. 5, pre-concentrator.

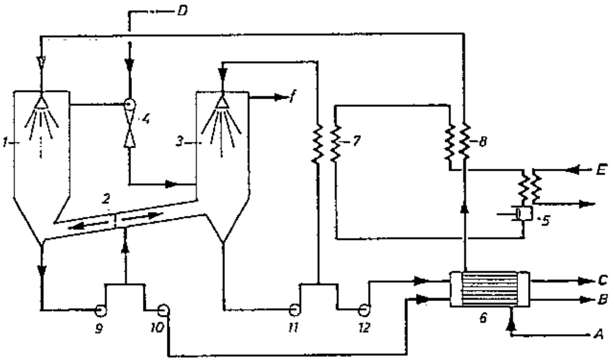


Fig. 14 Scheme of a sea water freezing plant for the practical production of potable water. 1, flash evaporator. 2, separation of ice and washing. 3, condenser and melting equipment. 4, steam-jet compressor. 5, refrigerating machine. 6, heat exchanger. (a) sea water. (b) concentrate. (c) fresh water. (d) operating steam. (e) cooling water. 7, 8, cooler. 9-12, pumps.

The process [4] is as follows: The sea water is pre-cooled in countercurrent to an ice slurry. It is then further cooled down to about −2°C in a compression refrigerating plant. The final chilling to the freezing temperature of about −3°C is effected by vacuum expansion in the evaporator where pure water crystallises out in the form of ice. The salt remains in the solution. Together with the concentrated solution the ice crystals are conveyed from the evaporator to a separating station which is shown schematically in Fig. 15. A part of the vapours arising from the vapour compressor is used for washing the ice. The remaining vapours are condensed in the direct-contact condenser by means of ice slurry. The water being circulated for condensation is re-cooled in the compression refrigerating plant.

In other cases [4] not water but a solution is used as a means of condensation; soda lye and lithium bromide liquor being well suited for this purpose. Without inserting a vapour compressor, the steam from the evaporator is absorbed by the solution. With an appropriate solution concentration the absorbing solution should have a temperature of about 20°C in order to absorb steam of −3°C. The water which is liberated during the flash cooling, is removed from the solution in a subsequent multi-stage evaporation plant.

REFERENCES

1. Messing, T., *Chem.-Eng.-Tech.*, 1958, 9, 589.
2. Hammer, H., Messing, T., and Schunk, H., *ibid.*, 1951, 21, 513.
3. Messing, T., *Kaltetechnik*, 1954, 6, 2, 41.
4. *Idem*, Dechema Monograph, Vol. 47, p. 793.

Ref No. Ka8/e Admin. Printed in England 3 69