Refrigeration Efficiency

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Introduction
Refrigeration systems often represent the largest electricity user in food and drink factories. Keeping refrigeration operating at best efficiency is very important but is often ignored because users are often unsure how to check their refrigeration plant performance.

To most end users the primary concern is plant reliability and, in particular, the ability to cool products to the desired temperature. If this is being achieved then it is often assumed that the plant is operating in a satisfactory manner. But is the plant running efficiently?

The assessment of refrigeration plant performance and the diagnosis of specific energy wasting faults is not easy. Refrigeration equipment is amongst the most complex found in food and drink factories – without a reasonably in-depth understanding of refrigeration it is hard to identify all the possible faults.

Measuring plant performance can be difficult, and experience has shown that two complementary monitoring strategies give the best results in ensuring maximum plant efficiency. These are:

- **Strategy 1: Indirect Assessment of Plant Faults**
  This involves assessment of the performance of individual items of plant, such as condensers, to identify specific types of fault that need to be remedied. This approach usually involves taking a "snapshot" of instantaneous data (e.g. temperatures and pressures) and comparing these data with "expected values". By understanding the interrelationship of different parameters being measured you can diagnose different types of plant fault. This strategy can be very powerful as it helps spot the exact cause of the wasted energy.

- **Strategy 2: Direct Monitoring of Performance**
  This involves measuring the power input into the plant over fairly long periods of time (e.g. weekly) and estimating the amount of cooling done in the same period, either by direct measurement or through calculation. This strategy allows you to build a comprehensive picture of plant performance over time.

Ideally, you should adopt both strategies, although Strategy 1 can often be adopted more quickly and with less investment in metering.

Strategy 1: Indirect Assessment of Plant Faults

The indirect assessment of faults uses instantaneous values; hence it can be done on an ad hoc basis as required. This could be in response to adverse data from direct monitoring of performance. Alternatively, if direct monitoring is not being carried out you should carry out indirect assessments on a scheduled basis e.g. weekly or monthly.

Taking a Data Snapshot
A snapshot of plant operating data, as illustrated in Figure 1 should be collected. Ideally the plant should be running under steady state conditions and, if possible, the plant should be run at 100% load as it is easier to interpret the data at full load. Avoid taking measurements within a few minutes of plant start-up as the

parameters may still be climbing towards a steady state value. If the compressor keeps varying in capacity, in response to load variations you may need to adjust a control setting to force the plant onto a steady full load.

For example, reduce the temperature set point of a cold store by a few degrees. If you do this, do not forget to return the control to the original setting!

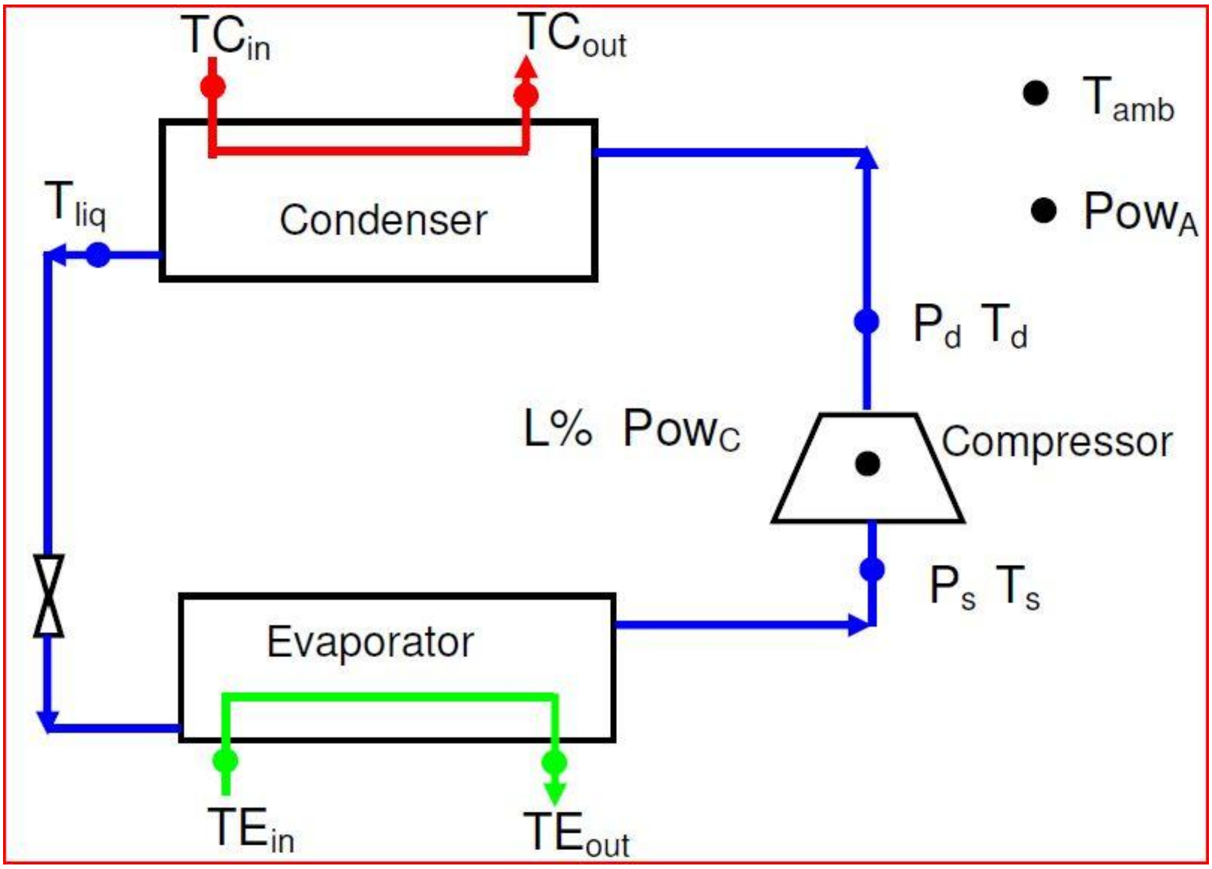

Figure 1: Plant operating data as illustrated should be collected. *Source: Institute of Refrigeration, UK.*

Compare Data Snapshot with Expected Values
This is often the most difficult step because you may be uncertain about expected values. Expected values for each snapshot parameter can vary with ambient temperature, cooling load and product temperature. You may need some expert help to establish tables of expected values. Fairly detailed plant design data is required to calculate expected values of temperature differences and pressures. Most of the required design data should have been supplied when the plant was installed and during commissioning tests.

Look for Fault Symptoms
The data collected should be assessed and a fault check should be developed. Each part of the plant can be considered separately.

- **Condensers:** Probably the most common faults are those linked to condensers – and they are usually fairly easy to spot. Inefficiencies linked to condenser problems always result in a compressor discharge pressure that is too high. A high discharge pressure reduces the system efficiency whilst at the same time it also reduces the amount of cooling being done. Most condenser faults are associated with a heat transfer problem that causes the condenser to operate inefficiently.

- **Evaporators:** Evaporator faults are also common and easy to spot. Inefficiencies linked to evaporator problems always result in a compressor suction pressure that is too low. A low suction pressure reduces the system efficiency whilst at the same time it also reduces the amount of cooling being done (sometimes by a significant amount). Most evaporator faults are associated with a heat transfer problem that causes the evaporator to operate inefficiently.
- **Compressors:** Compressor faults can be more difficult to spot. Compressor problems can relate to mechanical damage inside the compressor or to undesirable pressure drops due to blockage.
- **Expansion valves:** Expansion valve problems can be linked to the valve being open too much (leading to unwanted bypass of high pressure vapour through the valve) or being closed too much (leading to starvation of liquid feed to the evaporator).
- **Controls:** There are numerous controls on refrigerant plants that could be set incorrectly or that could be operating badly.
- **Cooling load:** The cooling loads themselves need to be checked to ensure they are not higher than necessary.

Strategy 2: Direct Monitoring of Performance

The direct assessment methodology uses "integrated data" measured over long periods of time e.g. kWh consumption of compressors. This data is used to estimate plant efficiency which can be compared to expected values.

The starting point is to understand how we express the efficiency of a refrigeration plant.

How We Measure Refrigeration Plant Performance
In simple terms, to measure the performance of a refrigeration plant we need to know:

- The amount of cooling being carried out, Q, measured in kW.
- The amount of power consumed, P, also measured in kW.

Then we can calculate the plant efficiency in terms of the ratio of cooling carried out to power consumed (Q/P). This is known as the **COP** or **Coefficient of Performance**.

In a refrigeration plant we are using power to move energy from a low temperature to a higher temperature. We are not "generating cold". We start by absorbing some energy at a low temperature (e.g. removing heat from a warm product placed in a cold store) and we then move that energy to a higher temperature so we can "throw it away" into the ambient. To move energy "uphill" from a low temperature to a higher temperature requires an input of extra energy. The amount of extra energy input depends mainly on the temperature difference between the cold end and the hot end of the process. If the temperature difference is around 30° C (typical for a chill store) then 1 kW of input power can "move" about 4 kW of heat up the mountain – this is a COP of 4. If the temperature difference is around 60° C (typical for a cold store) then 1 kW of input power can only "move" about 2 kW of heat up the mountain – this is a COP of 2.

Is Your COP Good or Bad?
Once you have measured your refrigeration plant COP, how do you know whether the performance is good or bad? Ideally we want the COP to be as high as possible, because that means we are getting more cooling for each kW of power input. So, what is a good COP? For a refrigeration plant this is not a simple question.

A plant with a low "temperature lift" will be more efficient than a plant with a high temperature lift. This is a fundamental aspect of efficient refrigeration plant operation. To minimise the temperature lift we want:

- The evaporating temperature of the refrigerant to be as high as possible.
- The condensing temperature of the refrigerant to be as low as possible.

The evaporating temperature is related to the product temperature – if you want to cool water to 5° C then the evaporating temperature must be below 5° C. However, it is also dependant on plant design and maintenance. If a water chiller producing 5° C water is evaporating at, say, -10° C then probably there is a design or maintenance related fault because the evaporating temperature is unnecessarily low.

Similarly, the condensing temperature is related to ambient temperature, but is strongly dependant on design and maintenance. There are many types of plant fault that lead to an unnecessarily high condensing temperature.

For one particular refrigerant plant many of the parameters that influence COP are fixed. In most situations the plant design is "fixed" and the product temperature is always approximately the same. However, if you measure a "snapshot" of the plant COP on two occasions it is normal that the COP could be significantly different. This is because the COP is very sensitive to:

- Ambient temperature – as described above, a few degrees difference in condensing temperature makes a big difference to COP. The condensing temperature is directly linked to the ambient temperature, which can vary by at least 10° C across a day and by 30° C seasonally.
- Plant load – under low load conditions the COP might be much lower than expected because of the influence of compressor part load efficiency and high auxiliary loads.

You Need to Establish a Range of "Expected Values for COP"
To interpret any COPs that you measure you need to have an idea of the "expected best COP" for a range of operating conditions. This involves a few difficult calculations so you may need to ask an expert for help. For a new plant you should ask the supplier to prepare a table such as the one illustrated in Table 1 – hopefully they will not charge for this if you build it into your specified requirements! For an existing plant a table like this can be calculated using design and commissioning data if available. Your maintenance contractor may be able to help with the necessary calculations.

Plant Cooling Load	Ambient Temperature [° C]	Expected Best COP
100 [%]	25	4.2
	15	5.9
	5	7.0
50 [%]	25	4.0
	15	5.5
	5	6.5
25 [%]	25	3.5
	15	4.8
	5	5.5

Table 1: Expected Compressor COPs (for a plant chilling a room to +2° C).

What Power is Included in COP?
A potential cause for confusion is what power inputs to include in the COP calculation. Compressor power is obviously included, but what about the main auxiliary loads such as pumps and fans used to run the evaporators and condensers? Many people refer to the "compressor COP", which only includes the compressor power. If we include evaporator and condenser auxiliaries then the COP is referred to as the "system COP" or "COSP". In all cases the COSP of an industrial refrigeration plant will be lower than the compressor COP. The impact of auxiliaries is especially important at part load, because the pump and fan power is often fixed at the "full load" value. This makes a lot of refrigeration plants very inefficient at low loads.

Setting up a Monitoring Programme
The direct assessment of overall plant performance is done using long term measurements of energy use; hence it is best done on a regular basis, with the key measurements being made at regular intervals. For most food and drink sites a weekly monitoring interval is appropriate. For very large systems it may be worthwhile doing daily measurements. The COP calculation is very simple to do:

- COP = Cooling carried out during period (kWh) / Electricity used during period (kWh)

The value of COP should then be compared with an expected value based on the plant design, the average plant load and the ambient temperature, using data like that illustrated in Table 1. The COP data (including both measured and expected values) can then be plotted on a week by week basis to try and spot adverse changes in performance. If the measured COP is lower than the expected value then you should carry out fault assessments (using Strategy 1) to try and identify the cause of the inefficiency.

Using Strategy 2, Direct Measurement of Plant Performance, seems a simple and effective approach. You measure the cooling carried out and the amount of power used and then calculate the COP. Measuring the power consumption is reasonably easy – although it does require kWh meters on the main electrical loads, especially the compressors.

Unfortunately measuring the cooling load is not always so easy to do – and sometimes is virtually impossible! For example if your main cooling load is a cold store, how do you measure the amount of cooling? You would need to measure the air flow and temperature difference across each cooling coil. This is impossible to do accurately and very expensive – that is why no industrial cold store users try to do it!
In some situations measuring the cooling load is easier. For example, if the cooling load is a flow of process liquid through a heat exchanger (e.g. milk through a pasteuriser) then you know the overall throughput (from production data) and the temperature difference can be measured fairly easily and accurately – so a cooling load can be assessed.

Options to Measure or Estimate the Cooling Load
There are 3 basic ways of estimating the cooling load:

1. Direct measurement. In some cases you can measure a flow rate and a temperature difference to directly calculate the heat load. This is most likely if a liquid is being cooled (e.g. chilled water or glycol in a secondary refrigeration circuit). This requires use of a “heat meter”, which is a device that combines flow measurement with temperature difference measurement to calculate heat flow. Unfortunately they are fairly expensive if an accurate measurement is to be obtained.
2. Estimate based on production throughput. If the load is dominated by process cooling then it is quite easy to relate the load to the tonnes of production. For example if you are freezing peas you can model the heat load in three steps: (a) sensible cooling of the pea from the inlet temperature to freezing point, (b) latent heat of freezing the pea and (c) sensible cooling of the pea from the freezing point to the storage temperature. This can be calculated once using reference books to obtain the specific and latent heat values – for example you can calculate the kWh per tonne of peas being frozen. Then you can use production data for tonnes of peas processed to estimate a cooling load. This can be a very reliable method if done with care. It applies to process cooling in most food and drink factories.
3. Estimate based on load modelling. Some heat loads are not related to product throughput. In particular this applies to cold stores and chill stores. In these circumstances you need to model the cooling load by listing the individual elements of the load and modelling these in relation to relevant parameters such as ambient temperature. This is probably the least reliable method, but the only option available for plants with large amounts of “non-process” load.

Example of Load Modelling
To estimate the cooling load through load modelling you need to identify each of the individual elements that make up the overall cooling load. Then you must identify what each element is dependant on in order to calculate the total cooling load in a given period of time.

This methodology is best suited to a simple spreadsheet model. To set up load models of this type you may require expert help – but once the load model is established you can use it for on-going monitoring for many years.

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