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Is Money Best Spent on Efficient Design or Service in Refrigeration

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Why you should attend:

- To get an overview of the key design and maintenance activities that are critical to achieving good system performance.
- To hear about the return on investment for both capital expenditure (CAPEX) and for service and maintenance activities and how the two are related.
- To hear about a holistic view of system performance and how this can be maintained and improved.

Abstract

In 2010 approximately 6.3 billion tonnes of food were produced globally, it is estimated that 2.3 billion tonnes of this require a refrigeration process of some sort. This has been increasing by approximately 10% year on year.

Refrigeration systems are responsible for consuming approximately 17% of all power generated globally. Assuming an average coefficient of performance (COP) of 4, we as an Industry are using around 4,500 billion kWh per annum and rejecting roughly 18,000 billion kWh of heat. Carbon emissions attributed to the operation of refrigeration systems vary depending on the energy source the system operator chooses to employ. As a sector, therefore, we are producing rather a lot of carbon, just in running our refrigeration systems. Arguably, not all will be efficient and from experience, most are not. Any decrease in efficiency just means greater amounts of cost, wear, and carbon emissions (ignoring altogether refrigerant type and leakages, which is a whole other topic of discussion, although related).

With the enormous increase in the adoption of heat pumps (a chiller working at a higher pressure) expected in the coming years, many of which will be attached to existing and new refrigeration systems to boost the Thermal Heat of Rejection up to a useful temperature for application in another process, it would be nonsensical to spend capital investment on an efficient solution without considering how effective your heat source is first, or would it?

Many industrial refrigeration systems have been in operation, and are expected to be so, for multiple decades, and in fact, I regularly come across compressors that are older than I. If one investigates the life cycle cost of these systems, the largest portion of the expenditure is energy, outweighing all other costs by a factor of 5 to 8.

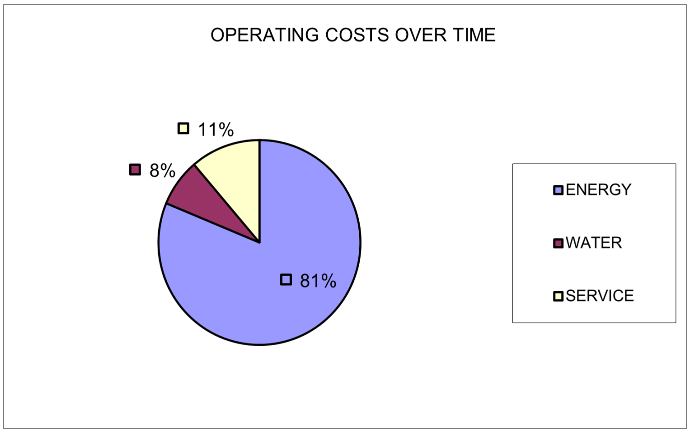

Figure 1: 1MW -22OC Freezer Store Operational Cost breakdown

When using an evaporative system to reject the heat from the refrigeration process, the greater the efficiency, the lesser the water consumption and effluent demand. With water availability being put under more and more pressure globally, we are now placing a strong focus on reducing system demand at the design stage; whereas historically, it was generally an afterthought, and arguably an inefficient refrigeration system uses more than it needs to.

Inefficiencies in refrigerated spaces, whether they be lights/computers left on, conveyor friction, motor efficiencies on drive lines, and of course staff running around, end up increasing the heat load and therefore increasing the demand on the refrigeration system. These inefficiencies, when combined with an inefficient refrigeration system all add up to the energy wasted from the system which is rejected as heat at the condenser.

The following paper attempts to explain a little more as to why designing efficient refrigeration systems is critical in solving many issues related to carbon, water, and energy reduction along with other additional costs which impact service expenses.

The argument: Is Money Best Spent on Efficient Design or Service in Refrigeration?

In my opinion, there is little point in increasing your CAPEX to build the world's most efficient refrigeration system, only to forget about it once commissioned and not maintain it in the appropriate manner. It will not be efficient or reliable for long.

1. Introduction

Being a bit of a geek, my first thought when being asked to write this paper and take part in the discussion arguing from a technical perspective as to why spending funds on efficient refrigeration design is more important than funds spent on service was that it should be relatively easy when looking into a life cycle cost calculation. Of course, I found myself arguing with myself because of course, both are of equal importance.

There is little point on increasing your CAPEX to drive efficiency up in a refrigeration system, which would arguably lead to larger/more efficient heat exchangers, larger slower running variable speed compressors and the correct type of condenser if they are not maintained or cleaned. For example, 1mm of calcium deposit on an evaporative condenser will easily eat up the cost of an entire year's Service Contract on a large installation.

Similarly, oil logging inside evaporators, or ice build-up on external heat exchange surfaces will equally have a negative effect. Pumps, circulation rates and the correct operation of the compressor itself, all have roles to play in system efficiency, but none will run optimally if they are not well maintained, even when the end user operates the system as originally designed and intended (often not the case).

Depending on the type of system, the arguments change somewhat, but all depend upon a simple fact. A refrigeration system is a closed loop (or at least it should be). Any energy entering the system will also leave the system, one way or another. As the second law of thermodynamics breaks down heat travels toward cold, energy will enter the system on the cold/low-pressure side of the system (intentionally or not) and it will leave (intentionally or not) if the temperature around it is either warmer or colder depending on which side you are looking at.

Heat we intend to enter the system on the cold side would be via evaporators and possibly intentional superheaters for example. Heat we do not perhaps intend to enter would be via poor insulation, or insulation breakdown leading to evaporation of more liquid or superheat of dry suction pipes. The first is controlled by efficient design and system control strategy, the other by proper maintenance.

To put some perspective on this point, if you have ice build-up on a suction pipe for example, it has twice the thermal conductivity of glass (0.25w/m.k) and half as much as cement (1-1.7w/m.k), but less than steel and copper (385w/m.k), obviously much less than insulation (eg. 0.035w/m.k). Therefore, if the vitally important vapour barrier breaks down on your pipework and you experience ice building up under and through your insulation, it is not a bad conductor of heat. Keeping the heat and moisture away from the places where it is not intended, is only achievable by a combination of efficient/proper design and proper maintenance.

To make some base calculations of efficiency on a system, I have chosen a refrigeration system operating with a suction condition of -30^{o}C and condensing at +32^{o}C, with a room temperature of -22^{o}C and an ambient wet bulb temperature of +21^{o}C and a load of 1,000kw. (Typical design considerations in the UK)

The system being considered is a pump circulated ammonia system with a pump overfeed of 3:1 and an evaporative condenser with a high-pressure receiver.

The application is something like a cold store, but to be honest this is irrelevant as I am considering the refrigeration cycle alone and not how often the clients' operators leave the doors open in the store for example, but I will consider the effect (snow/ice build-up) this has on our system.

Therefore, I will make some calculations and observations based on these conditions and the effect on running costs with different considerations and maintenance related issues.

Once all these are mapped, it builds up a stark picture as to where most of the end users' money is heading.

2. Evaporators

Evaporator design depends on the application, room shape, evaporator location, room type etc, but as this is where the energy enters the system and can be easily affected by external forces such as doors being left open, they are the first thing which tends to impact overall system efficiency.

For example, years ago it was standard to fit finned coils on ceilings and use natural convection to design evaporators. Due to the relatively poor heat transfer characteristics, a lot of surface area was required compared to the usual forced draught coolers we see today.

At the end of the day, if one needs a cold room, physics dictates that you need a colder surface to transfer the heat imposed on it.

Determining the required heat exchange surface involves many factors, but in essence, it is down to the logarithmic mean temperature difference (LMTD) and the heat exchanger's own thermal performance. Thermal performance is determined by many different factors, such as tube and fin design associated with air volumes and velocities across heat exchange surfaces, internal and external heat transfer rates, materials used, air conditions and lastly fouling.

If everything else is in place, the required heat exchanger surface area is calculated taking into consideration the design capacity and temperature difference.

The room temperature is fixed according to the user's requirements and evaporating temperature related directly to how large a surface area you wish to install. The closer the evaporating temperature is to the room temperature the larger the surface area of the heat exchanger will be. When evaporating temperature increases so does the suction pressure to the compressor. For every 1K you can raise the suction pressure, compressor performance increases by approximately 4%.

This 4% increase in compressor performance is seen as an increase in cooling capacity and Coefficient of Performance (COP). This is because the compressor has a certain swept volume, and as the saturated boiling temperature of the refrigerant increases, the specific volume of the vapour decreases, the density increases and the compressor's relative cooling capacity increases as it is moving a greater mass of refrigerant.

For example, 1,000kw of ammonia at -33°C boiled off, creates approximately 2,900m³/hr of vapour excluding flash gas (i.e. the compressor swept volume). The same 1,000kw of heat evaporating ammonia at -30°C would produce 2,550m³/hr of vapour. Therefore, having an evaporator which can operate in the higher evaporating condition would mean although you need a larger evaporator, you need a smaller compressor, and because it's operating at a higher evaporating pressure (1.19 bara rather than 1.03 bara) it does not have to compress the vapour as far to achieve the condensing pressure, therefore requiring less power per kW cooling. Less flash gas is also created at the expansion valve, which is a volume of vapour added to the evaporated vapour volume on the suction side of the compressor.

Reducing the liquid temperature before the expansion valve by subcooling reduces the amount of flash gas, and therefore frees up some of the suction capacity of the compressor for more "useful vapour" from an evaporator. This is one of the reasons for including things like economizers, compound compression and sub-coolers. Without this extra equipment, and in the example being considered, nearly a quarter of the swept volume of the compressor would be used just to deal with the flash gas.

Obviously, all these items cost money, but their effect on system efficiency can be substantial.

There is clearly a trade-off, as the evaporating temperature gets closer to the room temperature, you need proportionally much more surface area. And as the heat transfer figure reduces it becomes practically impossible and economically unviable to go larger.

Having said all that, once purchased and installed, these perfectly good heat exchangers/evaporators, economizers, and sub-coolers etc. are not going to perform very well and save you energy if they are covered in ice on the outside and coated in oil on the inside. Correct oil selection is an important factor to avoid fouling inside refrigeration systems.

For example, an evaporator with an air on temperature at -22°C and an evaporating temperature of -30°C with a circulation rate of 3:1, will need to evaporate close to -32°C to deliver the same capacity if it is covered with 2mm of ice. What tends to happen however, is that the air off temperature is not reached, because the suction condition remains the same in the compressor, and the room temperature raises a little, or the coolers have to run longer to compensate, as the same 2mm of ice has reduced the cooling capacity of the evaporator by nearly 16%.

Another issue which is not usually considered, is the fact that due to the over circulation rate of 3:1 being based on 50kw and fixed at commissioning, when the cooler is only delivering 42kw at best, the circulation rate has increased to 3.6:1, so in effect this additional over circulated liquid, ends up in the wet return, being sucked back through the risers and wet return pipework to the pump separator, increasing the pressure drop and worsening the evaporating pressure in the evaporator. A double impact, so to speak.

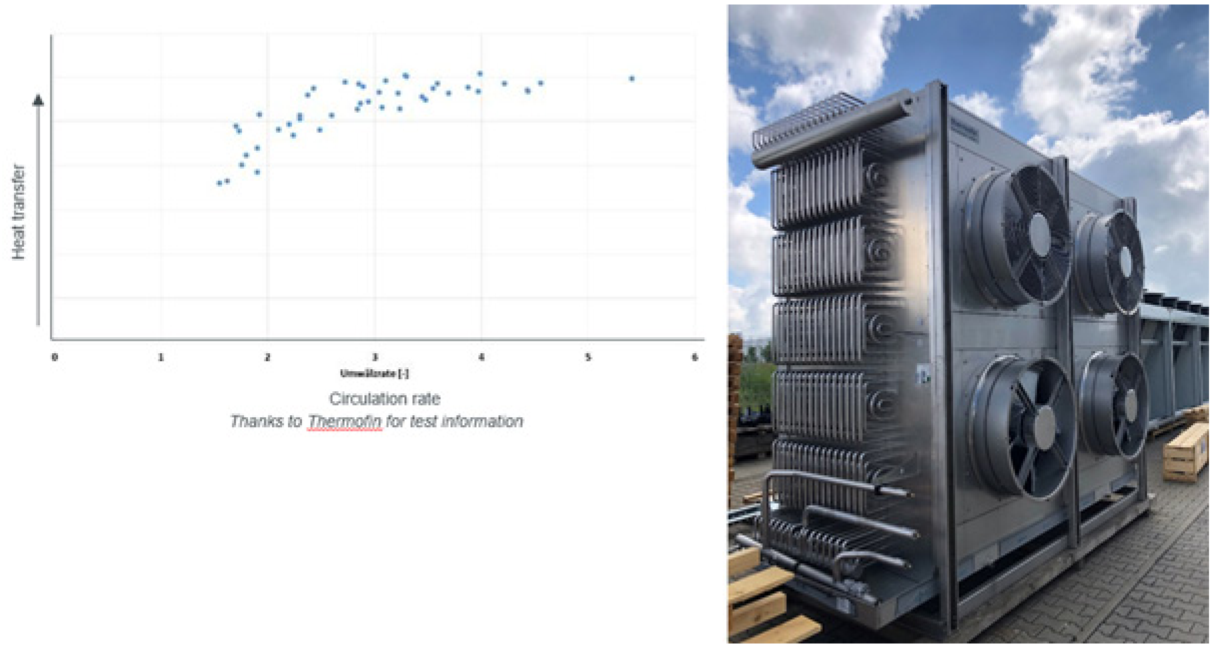

Figure 2: Standard bottom fed pumped over feed rate thermal performance on evaporator (without distributor)

Likewise, an oil film in the evaporator which increases a normal fouling figure to 0.0004 m2K/W would reduce the cooling capacity by 10%, so a combination of ice and oil really does hamper the efficiency of the system.

Although systems are hopefully designed to keep evaporators clear of ice and minimise oil contamination, it is widely acknowledged that it takes good service practices to ensure the system remains in optimal condition and operation throughout its lifetime.

Keep evaporators clean, in good working order and oil-free, and defrost them in a well-managed programme. When defrosting, keep the heat in the coil as much as possible, at cooler temperatures and do not allow defrost periods to extend past what is necessary. Remember, any heat and moisture entering the room from defrost must be removed again. However, if using hot gas to defrost an evaporator, your evaporator becomes a condenser and your condensing pressure will fall, so if controlled correctly, this can have a positive effect on your refrigeration compressor, and this will be covered a little later.

3. Compressors

As an employee of an international industrial compressor manufacturer, one might expect me to spend time discussing the pros and cons of various compressor technologies, but after far too many years on this subject I have decided to ignore the compressor type but focus on the system surrounding it, as I have often found people select compressor type for emotive reasons rather than fact, and so I would rather concentrate on items around the compressor which affect efficiency and service.

Starting on the suction side, suction strainers add pressure drops and should be clean. Similarly, on screw compressors and some manufacturers' reciprocating compressors these days, coalescent filters are used inside oil separators to reduce the oil carryover from the compressor package.

The coalescent filters are a compromise really by the compressor designer. Approximately 60% of the mass flow through a screw compressor is oil, therefore this needs to be removed. The compromise is, the better the effect of the filter, the greater the pressure drop and the greater the shaft power on the compressor. Over time, these pathways through the coalescers elements get blocked with oil deposits etc, and the velocity increases, causing a greater pressure drop and a higher oil carryover. This is where maintenance can come into play in either replacing or cleaning coalescers from time to time to keep the compressor running as it was intended.

There is also a return from the oil separator coalescer elements to the suction side of the compressor. This returns any oil which has been removed by the coalescer, back into the machine. This is normally controlled with a needle valve or a small orifice. Sometimes these lines can be blocked and therefore oil will collect at the coalescer and then get blown through and out of the machine into the system producing negative effects. These orifice/valves should be checked regularly but should not be opened too much as this is a direct return from the discharge to the suction side of the capacity and in some conditions could keep a compressor running irrespective if there is an actual cooling load on it or not.

Screw compressors, unless specifically ordered with variable Vi, compress to a certain pressure ratio. Therefore, if floating condenser control is used and the compressors' Vi position is set to summer conditions with larger differential pressures, the compressor will continue to compress to the higher pressure. As the gas expands as it leaves the discharge port, some of this energy is recovered, but not all. Auto Vi control moves the discharge position of the compressor automatically as the discharge pressure moves, keeping the correct compression ratio. The difference between having the correct ratio and not can be an excess in power consumption of up to 10%. Utilising Auto Vi in your system design represents a minor increase in CAPEX on a screw compressor application but is a good one to have, depending on operating conditions.

Some compressor manufacturers with fixed Vi have manually adjustable Vi slides which can be adjusted for example in the spring for summer running and in autumn for winter conditions. These adjustments should be carried out during a service visit. It is not unusual to come across a screw compressor which has been moved from a high-stage operation to a booster operation and the Vi position has been forgotten about.

Mechanical items such as motors, oil pumps etc should be in good working order. This goes without saying and is again a function of good maintenance.

Control and system design is also extremely important to ensure compressors are not cycling too often. For example, a variable speed reciprocating compressor running at a constant lower speed will run more efficiently, certainly last longer and cost less to maintain than if it were cycling up and down chasing load variations.

One also needs to bear in mind, especially with ammonia, that the "dry" suction line is full of saturated, un-superheated vapour. If the suction pressure raises because the refrigeration load has increased quickly, the compressor may not be following, and because there is a large thermal mass in the steel suction pipework as well as the suction side of the compressor itself, the vapour will condense on the insides of the "dry" pipework. This liquid will be sucked into the compressor, causing all sorts of issues. It's therefore important to control these capacity surges for both efficiency and equipment resilience reasons. A 3-5k suction pressure lift against 2 tonnes of steel suction pipework can condense a lot of liquid. In fact, it is about 5 litres at -30^{o}C. This effect can be even higher in heat pump applications because of the higher suction gas density; therefore a controlled, stable load becomes even more important.

Figure 3: This photo is the inside of a "dry" suction pipe where the suction pressure has risen by 3K. The lighter area and the "stream" along the bottom are the resultant condensed liquid being formed due to the rising suction pressure.

4. Condensers

The choice of condenser type really depends on location and individual requirements such as local water and effluent costs against power, capacity, and location. However, in the UK these days it's more common than not that designers are using dry, adiabatic and hybrid condensers over traditional evaporative types on industrial systems.

In a similar way to evaporators, there is an optimal/cost-effective design point where the larger the condenser, the more fan power it will consume to achieve the unachievable as the condensing saturated condition reaches the dry or wet bulb temperatures.

The difference with the condenser is, we can design an efficient condensing surface and install lots of surface area, but if it is covered with detritus or calcium, the heat transfer will dramatically drop off and the condensing pressure will rise, negating any benefit of the additional CAPEX spent.

As the condenser is the last heat exchanger to see the effects of any inefficiencies in the refrigeration system or process, from an energy efficiency perspective, I have always considered it as being the most important piece of equipment in a refrigeration system when considering both design as well as maintenance.

As with evaporators, condensers are heat exchangers and as such should be kept clean.

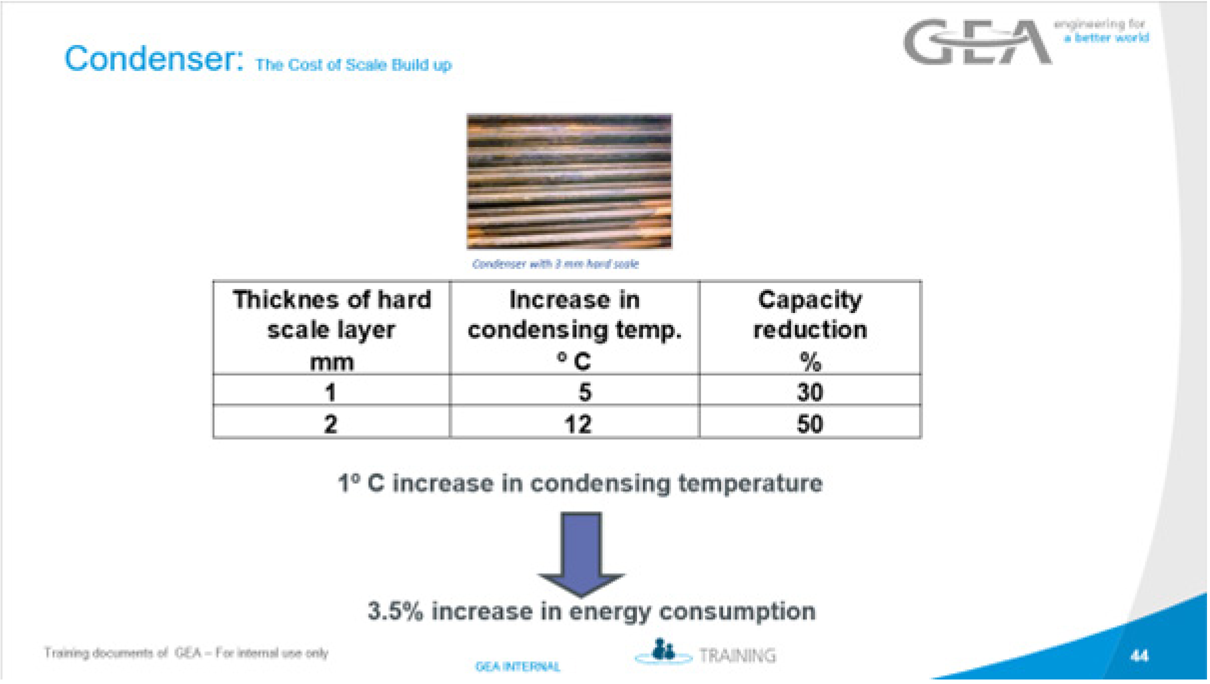

Figure 4: The effects of scale build up on the coil of an evaporative condenser

If the coil on the evaporative condenser is covered with calcium deposits for example, or the water distribution system is not correct, the effect will be this heat will be rejected to the ambient air with a higher temperature difference than design, and for every 1k, the condensing saturated temperature raises because of this “insulation”, the compressor draws approximately 3.5% more power for the given cooling duty. Again, it’s no good installing expensive heat exchangers and not maintaining them appropriately.

It is common practice these days to control condensers using “floating condensing pressure control”, effectively controlling the optimum temperature difference between the ambient temperature and the saturated condensing temperature, rather than at a fixed point. This requires additional control and sensors but can give good returns on investment if designed properly. Consideration must also be given to items such as expansion valves, discharge and hot gas supply systems and oil separators.

It’s a common misbelief that lowering the condensing pressure gives less heat for defrosting for example, but this is simply inaccurate. The heat given up per kg (latent heat of condensation) condensed is greater at a low pressure than a higher one. The issue is, as the pressure decreases in the discharge system, the specific volume of vapour increases dramatically. For example, the difference in a specific volume of the vapour at +35°C and +15°C on ammonia is appx. 45% greater at the lower pressure.

Therefore, if you try and lower the condensing pressure to these levels and the system hasn’t been designed for it, the velocities in all the pipes and oil separators will increase dramatically, so a point where defrosts take longer and oil is blown out through inadequately sized oil separators and coalescent filters.

An expansion valve orifice can merely be taken up one size to cope with the lower condensing pressure.

Remember, 50% of the year is night, and the other 50% is divided between seasons. For example, the effect on a compressor running at -10°C/+32°C during summer and -10°C/+15°C during winter is a COP of 4.13 and 7.1 on the same compressor, so a 42% efficiency increase. A little more CAPEX spent on these items can achieve a much better performance, and obviously, the condenser must also be kept clean throughout the year.

4. Conclusion

Refrigeration is a huge user of energy for the end user, and if you are a cold store owner it is not doubt by far your largest consumer.

There are many items of design (some covered above) which can raise the performance of these systems, and although they may involve increased CAPEX expenditure, they have quite good returns on investment. Although I was asked to argue the point for spending funds on efficient design, and I hope I have given some examples of this, these examples can be quickly negated by poor maintenance, so I fear the answer to the question, "Where should I spend my cash", it's always going to be - both.

I would however like to point out, you hopefully only spend CAPEX once, and if well-designed and maintained, our systems will outlast us. When spending a little extra for those few hours for your refrigeration service provider to check the correct operation of the system, it's arguably money well spent and is relatively inexpensive.

I always wonder why people spend so much per hour when they deliver their car into their annual service when the engine only ran typically for at best 1 hour per day doing the school run, where the "Engineer" only plugs it into a computer to tell you to top up with oil and perhaps change the filter, where the compressor which runs 24/7 and a system that makes you money gets quibbled over because the hourly rate for a real Refrigeration Engineer is half as much. Maybe that's a good point for discussion...

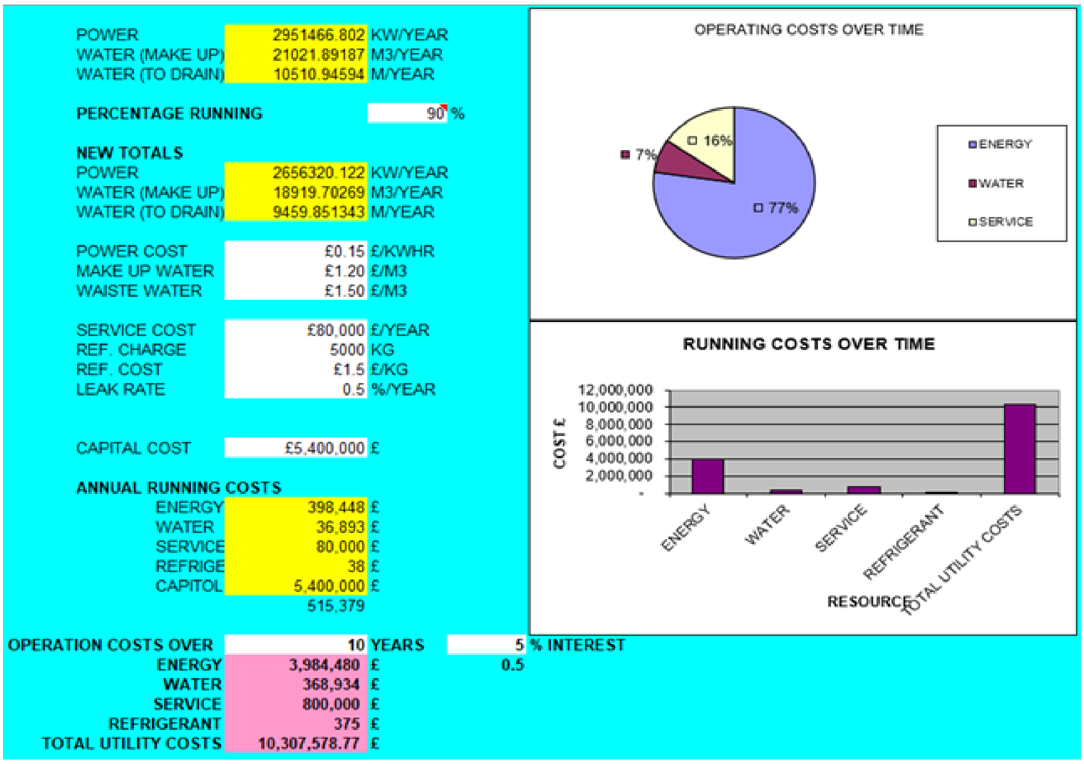

Figure 5: Life cycle cost calculation over 10 years based on 1MW -30ºC, two stage system with 20 Evaporators and evaporative condensers, with a "Guesstimated" CAPEX.

Figure 5 above details the results of a life cycle cost calculation with some estimations related to various costs, based on a 1,000kW design refrigeration load on a cold store with 20 evaporators operating with a suction pressure of -30°C, summer condensing condition of +32°C, with a two-stage, pump overfed system.

When one looks at the overall expenditure, excluding the CAPEX, the running costs are mostly made up of energy, and only 16% is accounted for with maintenance costs. If we said that half of the maintenance is components and the rest is labour, you could nearly double the amount of labour at the same cost of a 10% efficiency increase. With a correctly trained/experienced refrigeration engineer, you would only need to spend 10-20% more in hours if properly utilised to easily recover these additional costs many times over.

Proper maintenance should enhance the energy efficiency of your refrigeration system and is an inexpensive way of going about it, and now I am not sure if I am on the right side of the table….

References

Felix Webber. Thermofin GmbH;

Ken Picking. BAC