Open University of Cyprus

FACULTY OF PURE AND APPLIED SCIENCES

Master in Sustainable Energy Systems

Design of a cooling network for industrial Units

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November 2022

Master Thesis

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This postgraduate dissertation was submitted for partial fulfillment of the requirements for obtaining a postgraduate degree

at Sustainable Energy System

from Open University of Cyprus

November 2022

Summary

This study will present the distribution of cooling system in an industrial unit and we will try to find out unknown cooling capacity and flow rates to identify some issues for cooling load demand covering.

We will deal with the distribution circuit of secondary cooling medium and by using specific tools and equations to find the theoretical capacity of each consumer. Furthermore we will provide some upgrades, solutions for optimizing system's efficiency.

Acknowledgements

Special thanks to my supervisor professor Mr. Paris Fokaides and his research team to provide me with necessary tools, data and advices for the completion of this study.

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Chapter 1

Introduction

The world is facing lots of energy and environmental problems. The increasing of Green-House Gas emissions is taking the attention because this is the main threat for the environment. Climate has been rapidly changing in all over the world and significant amount of CO_2 are exhausted in the atmosphere.

Carbon neutralization has been proposed to guide economical construction including the protection of the environment and also conversion about energy management. Some regulations related with this issue trying to adjust emissions which are attributed at energy production systems that are using fossil fuels and cause air pollution, acid rain precipitation and ozone diminution.

Nowadays energy efficiency in industrial processes is considered as a major factor for economic growth, development and competitiveness. Based on that, manufacturers seek opportunities to improve their productivity and also reduce their operation costs. With current situation that energy production is much related with fossil fuels prices, some businesses are trying to invest into more effective and efficient energy technologies that will reduce operational costs but also keep product's quality level constant. Practices that following these high performance technologies can provide additional earnings for productivity efficiency and finally benefits for the environment.

Regarding the food production sector, a fundamental sector of energy consumption and more specific electricity consumption, is the refrigeration part. A lot of food production processes require many cooling loads in order to achieve the desired quality levels. Some times that means refrigeration equipment with high demand of energy consumption is used, so every taken measure for optimal improvement of energy efficiency and reducing electricity consumption of the cooling system will help the company to achieve environmental goals and also a step up for reliability.

Chapter 2

Literature Review

Since the industrial revolution, energy usage and energy production demands from humanity have been increased a lot. This increment although affect the environment and cause negative consequences on the environment.

More specific the massive extraction of fossil fuels and the combustion of them in order to produce energy cause problems in a regional and global range. Highly amounts of CO2 are releasing to the atmosphere and that has a major contribution in global warming because affect the world heat balance.

For this reason countries all over the world taking into account the energy efficiency as an important aspect of sustainability. Moreover European Union has started the implementation of the Green Deal which is trying to show the pathway for carbon neutralization by the year 2050. Countries are setting their national energy and climate plans in accordance to United Nations guidelines in order to reduce their CO2 emissions by 25%, increase the percentage of renewable energy sources contribution in various sectors such as electricity production, transportation, for heating and cooling purposes, support a variety to improve energy efficiency at houses and also public buildings, promote geothermal technologies for recovering energy, etc.

Industry sector is consuming huge amounts of energy for their processes, and these amounts continue rising to growth their field in manufacturing, mining, agriculture, constructions etc. Industries are consuming round to 35% of the total delivered energy globally and the amount increases by 1.4% average per year.

2.1 Energy Savings in Industry

Energy improvement is a basic and important aspect in order to address energy security and environment concerns also. At industry sector this can be achieved by managing the processes, by using more efficient technologies and by setting and implement policies and regulations.

The Energy Management is the strategy to guide using the energy where it is necessary and can be achieved by adjusting and optimize procedures and systems in order to reduce energy consumption demands. An annual general report of companies includes the sector of energy consumption and should mention in detail energy consumption, reducing measures and achievements. Energy audit is a must to implement an inspection and then by data analyzing find out all energy streams and the topics that can be improved and mitigate possible waste in order to achieve targets for energy savings. Additional benefits that come out from an energy audit is the reduction of operational costs and prevents failures and breakdowns from machineries, so it is improving the overall performance. In order for a successful implementation the top management involvement and commitment to this is very crucial.

Moreover, application of new technologies that are designated to reducing energy consumption is another step to achieve energy savings. By using for example a variable speed drive for rotating a compressor or a pump, it will be an advantage for the overall system performance instead of having an old system that starts and runs at full capacity all the time and then stops. Heat recovery units in a thermal system are very efficient when taking the waste energy from exhaust gasses and turn it to pre-heating energy. This kind of applications and many more have a purpose to improve conventional systems for saving costs, time and increase reliability of the company’s operation.

Furthermore in order to control energy consumptions from industry sector, lots of governments are creating policies related to energy management. These policies address issues where a problem occurs and covers all energy stages, from energy production to energy distribution and consumption. This can be taken from industry companies as a tool that will guide them to think about long term investments and create their strategic plan. This plan involve all relevant parties from the management team to the engineering team and also the accounting team in order to study all regulations and standards that must be followed, all existing fiscal conditions, all possible grants for investment on renewable energy sources and at the end setting the benchmarks and goals.

Finally, there also some trainings that will create the culture of energy saving within the company and also increase the awareness of the team that is involved to the key positions related with energy consumption. These courses will lead workers to housekeeping of their occupational area in order to eliminate inefficiencies related with energy but also unfavorable conditions and creating a safe workplace.

2.2 Refrigeration Systems

As we mentioned before, a fundamental part of electricity production in industries and more specific in food industries is consumed by the refrigeration or cooling plant. In countries all over the world large refrigeration systems are used in the food industry and factories for food processing and preservation, for providing cooling load to cold storages and also remove heat from production processes by using heat exchangers. Industrial refrigeration efficiency projects become very challenging because of the dynamic configuration, complexivity on their operations and their purpose and also their integration with other systems. Refrigeration systems can be found in a variety of sizes, arrangements and configurations. Depending on the system set up and its usage purpose, during high cooling demand comes in a relative pattern of electricity consumption producing necessary result but not always following the way to achieve ultimate operating conditions.

Refrigeration was developed in 19th century based on the vapor compression principle. First refrigeration device using this method was developed in 1834 and then applied to cold storage rooms and breweries. The constituent key components that make up an industrial refrigeration system are the compressors, the condensers, the expansion system of the refrigerant and the evaporator. This set of components also describes the refrigeration cycle, a design of a closed cycle vapor compression. This principle has not been changed a lot since the initial design. In addition various other items and devices are forming the control system of the equipment.

All the components have specific operation parameters depending on the refrigerant medium and system design such as the cooling demand, pressure and temperature in all stages of the refrigeration cycle and of course existing weather conditions which is inconsistent factor. In a different way operates the refrigeration system during summer and winter period. In order to achieve ultimate operation parameters there is a need to know and understand all the sub parts and devices and their interconnection and impact to the complete cooling system. For many occasions the manufacturer of each component is not the same and the operation conditions of each art may affect the others with the result of decreasing or even increasing the performance of the unit.

2.2.1 Refrigeration Compressor

The refrigeration compressor is the machinery that is taking the refrigerant in low pressure and low temperature from the evaporation process through the suction line, and transform it to a high pressure and temperature vapor. After that the vapor leaves the compression stage through the discharge line in order to go to the next step. Industrial refrigeration systems usually run with reciprocating (piston) and screw compressors. Piston compressors are very efficient at the partial loading demand instead of screw compressors that have high efficiency at high load demands. This is the component that consumes the higher amount of energy from the refrigeration system.

2.2.2 Refrigeration Condenser

Once the compressed vapor leaves the compressor stage through the discharge line, comes to the condenser. The condenser is the necessary device to absorb with some way the heat from the vapor that has been created through the compression step and release it to the atmosphere or transfer it to another system. With this way, temperature of pressurized vapor determines the temperature of the condenser system's medium and is cooled to the point that changing phase from vapor refrigerant to liquid refrigerant. This liquid then exits the condenser and goes to the expansion system through the liquid line. Common types of condensers are air-cooled that is using ambient air as condensing medium, evaporative that uses another system for heat exchanging and the water cooled system that uses water for example a cooling tower where the refrigerant goes through a coil and exchange its heat with the sprayed water.

2.2.3 Refrigeration Expansion

Refrigeration expansion system is the control device that is responsible to create the conditions for the high pressure liquid, loose its high pressure and by releasing it becomes a low pressure liquid but and also vapor, so is a mixture of two. This can be achieved by using an expansion valve which on the incoming side has the high pressure liquid in a smaller pipe and at the outgoing side of the device through an orifice which a small amount of refrigerant is passing, the pipe becomes bigger and there is rapidly decreasing of pressure and also temperature. This device is controlling also the flow that is entering the next step of refrigeration cycle. Selection of this controlling equipment is very important part of the design because it controls the mass flow entering the evaporator and must be the same amount and equal to the rate that is vaporized. That will prevent a liquid phase refrigerant within the suction line of the compressor because in this case damage will be caused to the compression system.

2.2.4 Refrigeration Evaporator

The evaporation step of the refrigerant is where there is the cooling need, for example remove heat from a place or remove the heat from a production process and the liquid refrigerant becomes vapor at low pressure. The absorption rate of heating and the rate that the vapor leaving the evaporator and goes to the compression step, determines the operation pressure. During the evaporation phase, in some cases frost may occurs in some surfaces and must be removed in order to prevent accumulation for blocking the normal flow. This process is naming defrosting and is part of the system that it uses hot gas after compression step to achieve frost elimination. At some other cases, electrical heaters or even hot water is used to do the defrosting.

2.3 Maintenance of Refrigeration Systems

Old equipment that has never been maintained properly further than cleaning and replacing some gaskets may increase the efficiency once they take retrofitting and overall maintenance service. Of course greater efficiency will provide new technology equipment but before start thinking the life-cycle of replacing the old with brand new device, for example manufacturing cost of a new system, disposal cost of the old system and refrigerant recovery systems that will be necessary, we need to cover every possible way for expand lifetime of existing equipment.

Mainly, maintenance for refrigeration systems is not acting proactively to mitigate the risk of a breakdown. Usually some of the maintenance procedures are being followed after a breakdown. In some cases where new installed units are under default liability period are taking maintenance properly but after expiration of the warranty nothing follows. Very little monitoring of operation parameters for such systems is recorded in order to prevent bad happenings and malfunctions or even maintenance records and energy consumption records. This will not help the strategy plan for maintenance taking into account running operation hours, complete history of the device.

Even the lack of data regarding maintenance and the relation with energy consumption this connection between maintenance and efficiency has been identified. In literature we found that studies proved that a rate of 50% of efficiency improvement has been recorded after the well maintain of a refrigeration system.

Firstly refrigeration system must be checked if there is any component with leakage. Further than that, technical team must ensure that all components are clean enough from dirty but also keep all flows in good condition for proper operation. Important thing is the correct amount of refrigerant that the system is charged. Provide also correct lubrication where is necessary is a must and check if there are abnormal vibrations.

In case of a massive leakage of the refrigerant, evacuation and good ventilation of the area is very important in order to reduce possible hazards and the occasion of exposure. Big concentrations of refrigerants such as ammonia and carbon dioxide may cause serious problems to humans in the area. The risk for any refrigeration system must be addressed through some control mechanisms that include also detecting possible leakages. They will ring an alarm in such case in order to inform the workers that something goes wrong and proceed with the appropriate procedures.

At the end, as we mentioned above, records must be kept for any action on the system, from operating parameters to maintenance services and corrective actions in case of problem.

Measurement of temperature and pressure in each stage of refrigeration cycle is good to be compared with the initial ones when the commissioning of the equipment took place and see if there are variances. A good monitoring of energy consumption will give significant findings on the operation conditions. After all a proper maintenance of the system will save some costs from energy consumption but also from repairing cost in case of a breakdown. This amount can be easily reached up to 20% savings on operational costs further than benefits related with energy savings. In many cases when refrigeration system failed, complete product line discarded because of quality issues.

2.4 Refrigeration Gasses

In general selection of the fluid that is used as refrigerant is depended from its thermodynamic properties. Their efficiency during refrigeration operation is related with the ratio of the critical temperature.

Early in 1900, the air conditioning market has started its developing for industrial purposes but also for domestic appliances. Halocarbons refrigerants rose as ultimate mediums to replace sulfur dioxide and methyl chlorine which were poisonous. They were compatible with existing equipment technology and had same power as refrigerants with previous ones. Also they were odorless and non toxic to human.

Many of them are toxic and harm the environment with the potential to destroy ozone layer. Additions and blends of hydrocarbons further than standard ones (R-134a, R-404a, R-407, etc.) to create less toxic refrigerants are the R-410a and R-417a solutions. These two can run in a higher pressure, with providing more capacity per refrigerant mass. On the other hand R-410a has high GWP (Global Warming Potential) compared to one unit of CO_2 and R-417a which has lower suction pressure and discharge pressure that may cause problem to the equipment. Another issue is flammability and for example gasses with methane or propane base such as R-32 refrigerant gas which is very common, is flammable under specific circumstances.

The amount of halocarbons as refrigerants that have been released to the environment due to leakages or due to emptying a system for maintenance purposes is estimated that exceeded by many times the total amount that refrigeration plants needed. For this reason lots of them and mixtures of them have been removed and limited gasses are used nowadays because of the legislation of gradual withdrawal.

2.4.1 Natural Refrigerants

Further water and air than can be used in some cases as refrigerants, there are some other gasses that can be used as refrigerants with very good cooling properties.

- Ammonia (NH_3)

Main properties of Ammonia as refrigerant gas (R-717) is the smell, that is very characteristic and pungent and also its toxicity not to the environment, its composition is hydrogen and nitrogen, but on humans. Nevertheless ammonia has been used for more than a century. Ammonia during refrigeration process has very good characteristics with high efficiency and in case of leakage it can be easily identified due to the characteristic smell. Because of its toxicity in humans, all ammonia appliances from installation, operation and maintenance must follow health and safety regulations and good practice codes.

- Hydrocarbons

Hydrocarbons can react very well as refrigerant gasses, with high efficiency during refrigeration cycle but there is one concern, they are flammable. For this reason also good practices must be followed when handling refrigeration systems that are using gases with basic composition of hydrocarbons. Once guidelines are followed then the risk level to use these materials is acceptable. A mixture of hydrocarbons and mineral oils can work in high critical temperature. Hydrocarbons are appearing regularly in small commercial appliances and less in big commercial systems.

- Carbon Dioxide

Carbon Dioxide has been used as refrigerant gas since the mid of 19th century. Its usage continued in marine sector instead of ammonia, until entry of halocarbons. CO_2 then became less efficient compared to other solutions because of its low critical temperature. After several years and the trying find a concept more environment friendly refrigerant gases, the usage of CO_2 improved based on new technologies founded that this gas reach the same level of efficiency as other refrigerants such as ammonia and halocarbons. It can be used in cascade systems, combined with ammonia due to its low evaporation temperature below of $-35\ ^oC$.

2.4.2 Environmental Impact of Refrigerants

Ammonia and Carbon Dioxide are environmental friendly refrigerants and they have no impact to the ozone layer. Based on Montreal and Kyoto protocols lots of countries committed for reduction of chlorofluorocarbons (CFCs) and hydro chlorofluorocarbons (HCFCs) usage and go to zero quantities by the year 2030. The total equivalent warming impact and life cycle climate performance indicators illustrate the importance of the energy efficiency and rate of low global warming potential values of each refrigerant emission. Global warming potential is measuring how much energy and emissions of 1 ton of the examined gas compared will released to atmosphere over a period of a century compared to 1 ton of CO2 emissions for the same period. The ODP indicator is ration of the impact on ozone of a chemical compare to the impact of similar amount of FREON gas, CFC-11.

Below the tables that present the environmental impact of natural refrigerants and the most common used synthetic refrigerants.

Refrigerant	**GWP**	**ODP**	**Flammability**	**Toxicity**
Ammonia	0	0	1	3
Carbon Dioxide	1	0	0	0
Propane	3.3	0	4	2
Isobutene	3	0	4	1

Table 1: Environmental impact of Natural Refrigerants

Refrigerant	**GWP**	**ODP**	**Flammability**	**Toxicity**
R-12	10600	1	0	0
R-134a	1430	0	0	1
R-22	1700	0.05	1	2
R-404a	3260	0	0	1
R-507	3300	0	0	2

Table 2: Environmental impact of Synthetic Refrigerants

Ammonia and Carbon Dioxide refrigeration systems in industry field can cost less than systems using synthetic refrigerants from the design phase, to the installation and also operation phase. In terms of thermodynamics ammonia and carbon dioxide have higher efficiency and use lower level of energy compared to the synthetic ones.

2.5 Alternative Refrigeration Systems

The majority of refrigeration systems are using a reversed Rankine Cycle which is an idealized cycle of thermodynamics and describes the process that heat / thermal engines allow mechanical energy to be extracted from fluid while it moves between a heat source and heat sink.

There are although some alternative refrigerating systems that use the Rankine cycle with refrigerant mediums which have limitations on their applications. Some other systems that follow a complete different approach will be described below.

2.5.1 Sterling Cycle Refrigeration

Sterling Cycle was invented in 1812 by Robert Sterling in order to produce a much safer, external combustion engine than the crude steam engine. As refrigeration system is very efficient but on the other hand is very complex principle. Sterling refrigeration system includes a combination of compression pistons, displacer pistons, heat exchangers for regenerations and various other devices for regulating operation parameters such as pistons movement. In general hydrogen gas is the ultimate fluid element for using a sterling refrigeration cycle, and that because hydrogen has low weight. Another element that is used for this king of systems is nitrogen because it is cheap as material as and safer than hydrogen. New technologies and methods are trying to develop new sterling cycle designs in order to improve efficiency.

2.5.2 Vortex Tube Refrigeration

Vortex Tube is very simple as device but its operation is very complicated. Compressed air is passing this tube which has a baffle plate inside. Purpose of this is to separate the cold and hot air and guide these two forms to exit from a different direction through the tube. This separation of low and high energy loaded air can decrease the temperature and produce cooling load. It is not very efficient as procedure but as we mentioned before it has a simple design.

2.5.3 Magnetic Refrigeration

Magnetic Refrigeration is another technology that it is based on the magneto-caloric effect. This technology can be used to achieve extremely low temperatures. A magneto-caloric element is increasing its temperature when there is a magnetic field application. Once this field is removed then the element is returning to its first form by reabsorbing the excessive heat. In order to achieve refrigeration, coming from this process, material is forced to get off the heat by radiation way and by removing magnet field, the element drops its temperature further than the temperature has in its original phase.

2.5.4 Acoustic Refrigeration

Acoustic refrigeration system takes the advantage of sound waves to reverberating and converts a differential of temperature to a mechanical energy or a mechanical energy to a temperature differential. This acoustic energy that is travelling through the gas can produce cooling because of the pressure fluctuations and variations of the gas inside the refrigeration pipe. Common fluid element that is used for this kind of application is air or noble gasses.

2.5.5 Thermo-Electric Refrigeration

Thermo-electric Refrigeration is a method that trying to extract heating energy outside from an insulated chamber by pumping it electronically. Thermoelectric modules are constructed from dissimilar metals that are bonded together and connected electrically. By force electricity current to pass between them heat is transfer from the first material to the second one. Achieving this will lead to reduce the chamber's temperature below of its external conditions. This process is based on the Peltier theory or Peltier effect which is the inventor of this technology in 1834.

2.6 Renewable Refrigeration Systems

Generating energy from sustainable resources to serve refrigeration purposes is a must on the design nowadays because of their environmental aspect of view. Refrigeration systems that are tend to operate with zero carbon emissions are based on the usage of renewable energies such as wind, solar and geothermal energy. These kind of technologies are often provide fixed or a predictable kind of consuming price during the lifetime of the refrigeration system compared of the inconstant price of energies that come from fossil fuels involvement. Also gives the sense of energy security and increase job vacancies in order to develop and implement refrigeration systems.

2.6.1 Refrigeration from Solar Energy

Solar energy is a huge and inexhaustible source of energy. It can easily cover lots of energy demands of the world which is increasing year by year and is much cleaner than most of the conventional sources such as fossil fuels.

Solar refrigeration systems are using electrical power that is produced by solar systems or by using solar thermal collecting systems to collect heat from sun radiation. All these systems can be classified in three main categories.

- Photovoltaic panels refrigeration systems

  By using photovoltaic panels and semi-conducting elements, solar radiation is converted to electricity. The PVs produce direct current (DC) kind of electricity energy and easily handle the operation of the refrigeration DC system or by using a kind of converter to operate more common refrigeration systems with alternative current (AC) electricity. For example this energy will drive the compressor to circulate the refrigerant and cover with this way part or full of the demand of electricity power.

- Solar Mechanical Refrigeration

  Solar mechanical refrigeration generally uses conventional compression system which is driven by a mechanical power but this power is produced by a solar generated heat power cycle. In this type of refrigeration system the required power system to operate the compressor is following a solar system based on the Rankine Cycle. In this application, the fluid element is becoming vapor at elevated pressure by using heat exchange with another element heated by solar radiation through the sun energy collector devices. The efficiency of this process is increasing by the high temperature heat that is collected from solar thermal panels, so thermal panels that have sun trucking system and can rotate based on sun position on the sky can massively gain more power than constant ones.

- Absorption Refrigeration System

  Absorption refrigeration System using a technology that is designated to reduce energy consumption of the cooling system, address the parameters of energy crisis and meet some environmental objectives. These systems have increasing interests for development because of their advantages compared to the conventional refrigeration systems.

  Absorption refrigeration systems are using the same process with the conventional system of refrigeration following the compression, condensing, expansion and evaporating cycle.

  The bigger difference between these two systems is the methodology of the process during the suction and compression of the refrigerant medium. In the standard system the compressor is sucking the vapor refrigerant from the evaporator and compresses it until it reach a higher pressure and force it to move through the refrigeration pipe circuit. As for the absorption refrigeration system the compression of the vapor is handled by two separated equipment, the absorber device and the generator. Purpose of the absorber, which is driven by the heat instead of an electric motor, is to ensure that the fluid element will flow through the system and the generator to increase its pressure to a higher level.

  On the other hand an absorption refrigeration system needs more space than a conventional refrigeration system because of its bigger required units and larger size in general.

2.6.2 Refrigeration from Geothermal Energy

Geothermal energy attracts the attention to because the ability to use technologies that requires lees electricity consumption and thus lower carbon emissions. Thermal energy that comes from earth’s ground can be extracted and through utilization systems use it as an organic energy source for heating and cooling. Geothermal system takes the advantage of temperature difference between ambient and subsurface soil conditions and then exchanges this heat to gain energy. Usually is classified in three subcategories. Hot dry rock geothermal energy, hydrothermal geothermal energy and finally shallow geothermal energy. Finally it can be easily combined with other technologies that are using different energy source to increase the efficiency of a refrigeration system.

2.6.3 Refrigeration from Multi-Energy Complementarity

A combination of geothermal energy and solar energy as we mentioned above, can reach up to a better efficiency and performance technology and system design, and achieve a zero carbon emission standards for a refrigeration system. By the combined operation of these two system categories, better results will be taken instead of using these technologies separately. That automatically means, system installation, operation and maintenance have lower cost because of the needed parameters must be followed.

2.7 Secondary Refrigeration Systems

The difference between direct and indirect cooling systems resides in the separation between primary circuit where there is the cooling production and the secondary circuit where the cooling is giving its load.

Functions of the indirect system circuit are for the heat transfer fluid to transfer the cooling load for the purpose that we need to run the refrigeration system and to protect the complete refrigeration system. In terms of corrosion protection at very low temperatures, systems are reacting differently so by separating the main refrigeration system and have secondary system using protection mechanisms may prevent total system breakdown.

Advantages from usage of an indirect refrigeration system are many and some of them are presented below:

- Reduce the amount of refrigerant fluid
- Reduce the refrigerant system size
- Reduce the refrigerant system installation cost in terms of pipelines and circuits
- Reduce the leakage occasions of the primary refrigerant
- Reduce complexivity of selecting the proper refrigeration system and create the potential of future modifications if needed.

One of the most common secondary coolants that is used in indirect systems is the water or a mixture of water with another fluid that has the proper heat conduction properties. This kind of mixture can be a glycol compound where the advantages of it are related with its anti-freezing properties. Water starts freezing at 0 ^{o}C so in refrigeration system there is a danger of freezing, block the nominal flow with the result to stop refrigeration system operation. A water-glycol mixture at a volume composition of 70% - 30% can run at -14 ^{oC} without freezing problems. An additional advantage is that the glycol mixture can remove large amount of heat where there is a need to exchange the load in less time. Finally the presence of a glycol in the whole circuit prevents the appearance of algae within the system, which is one problem that affects the heat transfer and equipment efficiency. Most common glycol mixtures are propylene-glycol and ethylene glycol.

In order to achieve ultimate and coldest temperatures that will serve the purpose of the cooling system, calculations must take place for the proper ratio for the mixture of secondary cooling system, between glycol and water. If the secondary system is used inside, then less propylene-glycol composition is needed than an exterior usage application. This part of design may affect the overall efficiency of the system and that because with higher quantities of propylene glycol heat exchange coefficient of the mixture is reduced and with very low glycol volume composition may the mixture freezes, cause problem to the heat exchange device between primary and secondary fluids and even bursting the piping material.

2.8 Heat Exchangers

Heat exchanger is a system that is responsible to transfer the heat between two or more fluid elements with the ability not to mixing them. Because of the global energy consumption and financial aspects of a system that consume energy, technologies and design of such systems have been developed based on the higher efficiency in order to reduce possible energy losses through the heat exchange process.

The heat exchange process may include also element's phase transformation within the device and that is the reason of name and separates them to recovery systems, boilers, condensers, evaporators, etc. In addition based heat transfer surface heat exchangers can be classified in the below types.

- Shell and Tube heat exchanger

  Shell and tube heat exchangers are the most common type. Their design is consists from a single tube or a set of parallel tubes (for the first fluid element), that are enclosed within a bigger vessel (for the second fluid element).

- Plate heat exchanger

  Plate Heat exchangers uses lots of thin metal plates that are bundled together. Each pair of this kind of plates is creating set of channels where the fluids running and passing without getting mixed but only exchanging energy. Because of the fins, gaskets and spacers between the metal plates this kind of equipment allows multiple flow configurations and also more than two fluid elements for heat exchanging.
- Regenerative heat exchanger

  Regenerative heat exchangers are mainly used where the temperature of the fluid elements is not constant and there is a requirement of a compact design. Temperature variance can be neglected if there is metallic regenerator with comparatively smaller wall thickness than the storage material is used.

- Tubular heat exchanger

  Tubular heat exchangers are the simplest form of all these equipments and consists two concentric and coaxial tubes for carrying the two fluid elements. Heat exchangers that have double piping design are very cheap and consists good design choice for smaller appliances.

Chapter 3

Cooling System in a Brewery

In this study, we will deal with a refrigeration plant design case of a brewery. In general after several upgrades to increase production efficiency, there is also a need to adjust the cooling circuit and network that feeds the sub production lines of beer processing.

3.1 Processes in a brewery

A brewery factory is producing a variety kind of beers. Basically it takes malted barley as raw material and by using pre-treated water brings them to the milling process to create a mixture of high yield of extracted substances within the mash tank. By heating up the mixture the starchy malt is hydrolyzed by using more hot water for better efficiency. The next step of the brewery production is lauter tank where the mixture is increasing again its temperature and finally separates the liquid from the malt grains, a kind of filtering system. By this process the liquid product that is called wort, is going to the last stage of production, the wort kettle. At this phase the wort is prepared for it boiling procedure after adding some other ingredients, such as hops, syrups etc.

During the boiling stage, temperature of the wort is reaching up to 100 ^{o}C in order to be sterilized which means massive needs of energy. When the worting out-comes the boiling tank, the mixture must get cooled to 15 ^{o}C in order to proceed to oxygenated and with the addition of yeast.

Then follow the second phase of production which called fermentation process. During this process where cooling load needs to decrease the temperature of the wort step by step close to 5 ^{o}C in a duration of approximately ten days, lots of chemical reactions taking place and metabolized the fermentable sugars to produce alcohol and CO_2. Carbon Dioxide quantities can also be retrieved by a separate system after necessary treatment, in order to liquefy it and store it in very low temperatures for a later usage during various steps of the production, from beer processing to packaging.

The third step of the production is called beer processing. At this stage the mixture that is inside the fermentation vessels has required concentration of alcohol and it is ready for further treatment. Firstly must remove the remaining yeast from the product by using specialized equipment for this purpose like centrifugal separators. This method also needs cooling load in order to decrease the temperature close to zero and then keep the product in a constant temperature and prevent any shocking that will affect the quality in a later stage. After separating the yeast from the beer, another filtration process is following in order to polishing the final product and removes any unnecessary remaining particles. Also cooling capacity is needed there to keep constant temperatures during the process.

Last step on this stage is the dilution with deaerated water in order to get the optimum composition in alcohol and create the final product. To reach desired quality of deaerated water, water passes through a heat exchanger to increase its temperature in order to force to loosen molecular bonds between oxygen and hydrogen. Lastly the diluted product goes to the storage tanks where the temperature again is remaining constant supported by the cooling system.

Final stage of production in a brewery factory is the packaging phase where the final product packaged and get ready for the market. In order to ensure the quality of the beer and extend its validity period of consumption, pasteurization process is need, so heating loads and cooling loads for this process is needed too.

3.2 Case of brewery cooling system

The specific brewery has a cooling plant capacity of 1200KW and runs with propylene-glycol mixture and ammonia NH3 as a refrigerant medium.

NH_3 (Ammonia) side is following the refrigeration cycle with two piston compressors to increase the temperature and pressure, then goes to water cooling towers for condensation, after that through the expansion valve to the separator and finally to the 1200kW heat exchanger with the propylene glycol.

Propylene-glycol is preferable on food industries in order to avoid contaminate the product through the temperature / heat exchange process.

Initial design of the system is to provide propylene-glycol mixture to the whole factory at -5^{o}C for production cooling needs and return back to the refrigeration system at 0 ^{o}C. After all upgrades to the beer processing production lines, glycol cooling circuit return at even up to +5^{o}C, and that affect all stages of production. When the glycol mixture starts to lose its cooling temperature and slowly increase at a higher level than the designated one, ammonia side starts working at a higher range of capacity and if the demand is at the top pick, can-not balance the cooling circuit with required temperatures.

Once the refrigeration plant starts running at full capacity and during the summer period when ambient temperatures exceeding 40^{o}C, that cause high energy / electricity consumption, high water demands for the ammonia condensation process and at the end increasing the production cost. Propylene-glycol system feeds with cooling energy various production processes until the final product goes for packaging.

Firstly there are more than 20 fermentation tanks of 70m^3 'beer' capacities each. There are another 10 beer storage tanks of 100m3 capacities each, there is a need of cooling during draft beer packaging after pasteurization and during the beer processing procedure of course. During this production process there is a need to decrease beer temperature when removing the yeast from the beer, there is a need for even lower temperature when the beer is running through the filtration process and finally when there is a production of low oxygen concentration water for dilute high gravity beer liquid.

3.3 Software Tools

In order to proceed with further analysis, simulations and results extraction, some software tools are needed. For this purpose we are presenting below the main two

- Aspen Plus Software

  In industry, engineering teams are usually use software programs in order to solve complicated problems in order to spend many dates with hand calculations to get results.

  Aspen Plus software is a program simulator that allows predicting behaviors of various processes by using basic engineering relationships and equations that are related with mass and energy balances and thermodynamic principles.
  It allows custom designs and flow-sheet construction on its platform with a variety of inputs to create a totally new system but also increase the percentage of closeness to real conditions and real situations on existing system, in order to optimize the design of crucial operation parameters.

  Selecting the proper physical property method for analyzing process depending its category and nature is very important taking also into account chemical and thermodynamic properties.

  Basically can handle the below complex processes:

  - Multiple column separation columns
  - Chemical reactors
  - Distillation if chemically reactive compounds
  - Electrolyte Solutions (Chlor-Alkali Industry)
  - Complex Recycle – Bypass stream in process

- Sankey Diagram creation

Sankey Diagram is a flow chart diagram where the width of the lines is proportional with the flow rate. They emphasize the major flow rates or transfer rates of a system and helps to identify the contribution and the percentage of each separate flow comparing it with others flows and also the total. This kind of diagrams can easily visualize the energy accounts, material accounts at a cost breakdown in general.

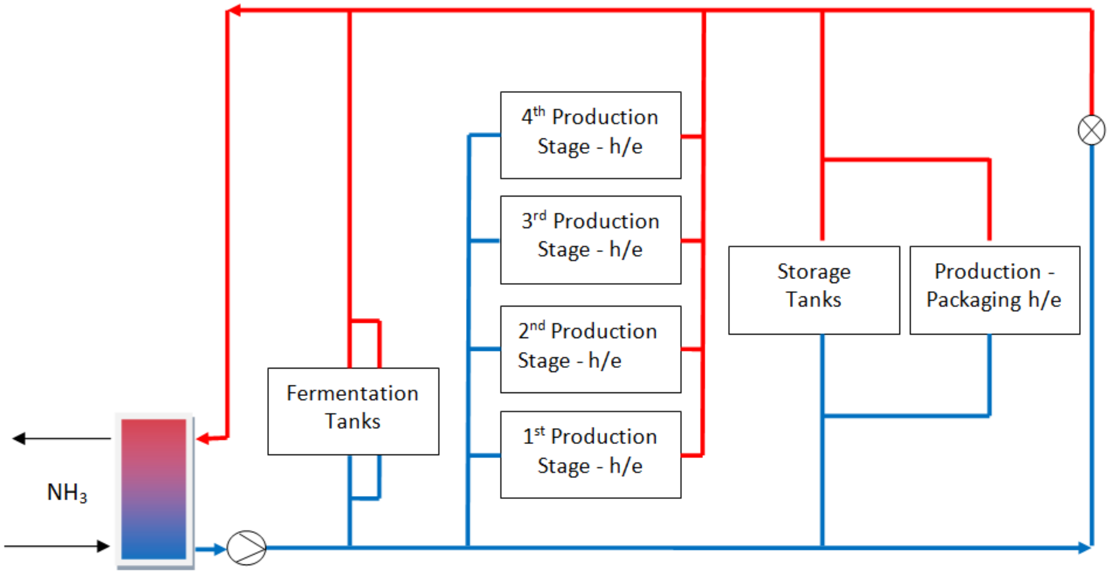
Chapter 4

Theoretical approach and data analysis

Because of measurement instrumentation lack in terms of flow rates in each division / consumer, we will try to estimate in this study the theoretical mass flow rate that must has each heat exchanger depending on manufacturer technical specifications.

4.1 Flow Diagram of Propylene-Glycol mixture

The pipeline flow diagram of the propylene-glycol mixture from main heat exchanger with ammonia until every consumer is presented below.



Picture1: Propylene-glycol flow diagram

Propylene-glycol / water mixture is taking cooling load from the NH3 heat exchanger and then through a pumping system supplies all necessary equipment that there is a cooling demand.

4.2 Calculations for mass flow rates

For each 'consumer', heat exchange process, we will run a thermodynamic analysis, calculate the mass flow rate and then present the Sankey diagram.

Cooling medium, as we mentioned above, is a mixture of 30% propylene glycol and 70% of water by volume. Heat Capacity of propylene glycol is 3.915 KJ/KgK and for water 4.187 KJ/KgK. As for density propylene glycol has 997 Kg/m^3 and water 1040 Kg/m^3.

Cooling loads for each division is presented at the below table based on the technical specifications for each equipment.

Equipment	**Cooling Capacity (kW)**
Glycol Supply	1207
Fermentation Tanks	265
Storage Tanks	15
1st Production Stage	50
2nd Production Stage	160
3rd Production Stage	320
4th Production Stage	352
Production Package	45

Table 3: Cooling Loads

Taking the assumption of Temperature differential between inlet and outlet of each heat exchanger at glycol side ($\Delta T=5^oC$), we can calculate the initial mass flow rate for each division.

Equation:

$Q = \dot{m} \times Cp_{glycol} \times \Delta T$

⇨ $\dot{m} = Q \ / \ (Cp_{glycol} \times \Delta T\ )$

For Glycol Supply: $\dot{m}$ = 1207 kW / (3.915 KJ/KgK x 5 ^{o}K) = **61.66 Kg/s**

As for the 'consumers',

For Fermentation Tanks: $\dot{m}$ = 265 kW / (3.915 KJ/KgK x 5 ^{o}K) = 13.54 Kg/s

For Storage Tanks : $\dot{m}$ = 15 kW / (3.915 KJ/KgK x 5 ^{o}K) = 0.77 Kg/s

For 1st Production Stage: $\dot{m}$ = 320 kW / (3.915 KJ/KgK x 5 ^{o}K) = 16.35 Kg/s

For 2nd Production Stage: $\dot{m}$ = 160 kW / (3.915 KJ/KgK x 5 ^{o}K) = 8.17 Kg/s

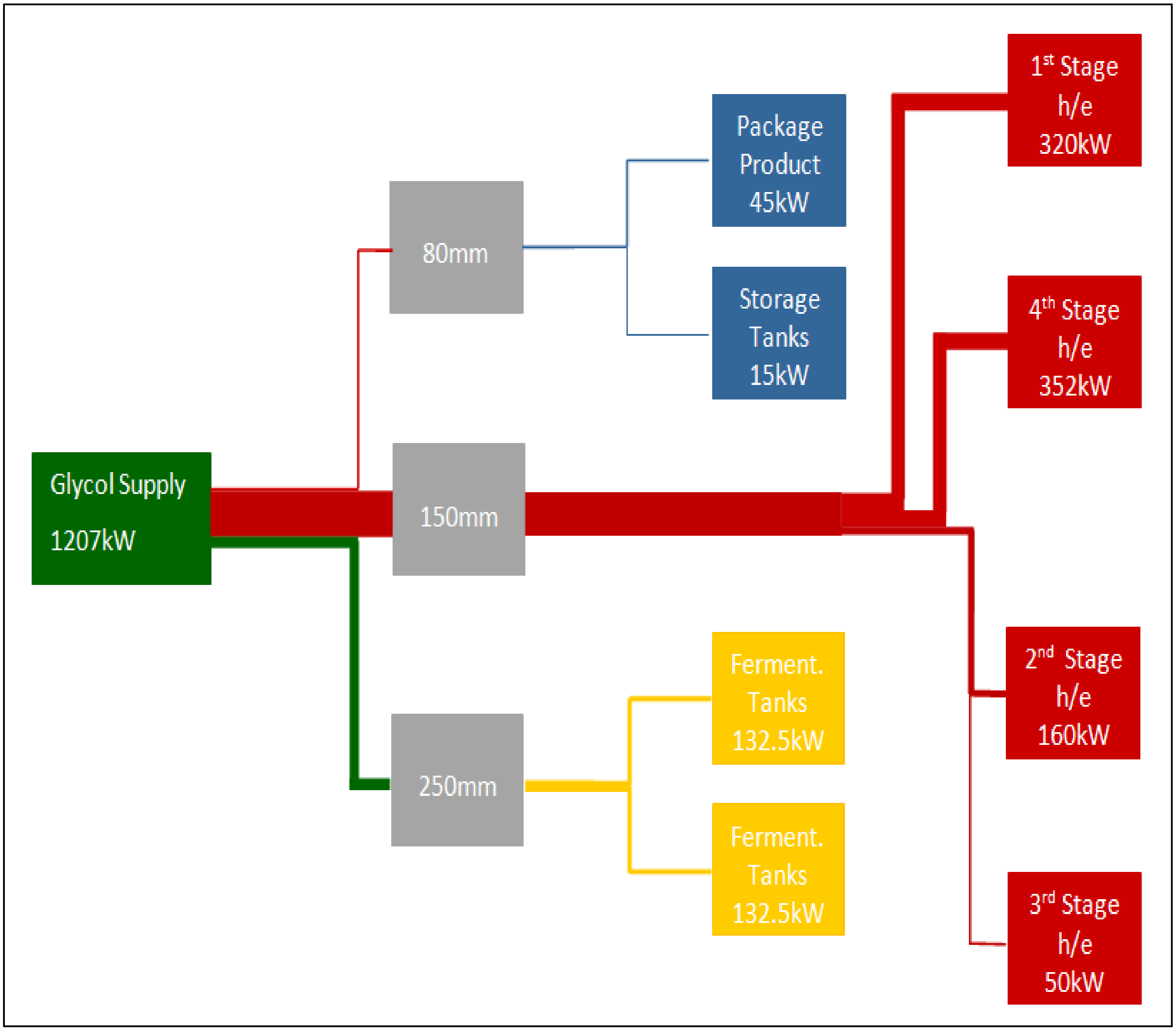
For 3rd Production Stage: $\dot{m}$ = 50 kW / (3.915 KJ/KgK x 5 ^{o}K) = 2.56 Kg/s

For 4th Production Stage: $\dot{m}$ = 352 kW / (3.915 KJ/KgK x 5 ^{o}K) = 17.98 Kg/s

For Production Package: $\dot{m}$ = 45 kW / (3.915 KJ/KgK x 5 ^{o}K) = 2.3 Kg/s

4.3 Sankey Diagram

As we mentioned before the Sankey diagram is showing and loading the most important flows on the system. Clearly we see that the three main consumers are the first, second and fourth production stages where the demand on cooling is high and at the same time.



Picture 2: Sankey Diagram of glycol mass flow rates

4.4 Heat Exchangers analysis

By using Aspen Plus program for heat exchanger analysis we will run some data for three heat exchangers at the production stage 1, production stage 2 and production stage 4 that demand is high and at the same time. In addition we are making the analysis placing existing data for the cold stream with inlet temperature at -5 ^{o}C and the outlet temperature at 5 ^{o}C. In addition we are placing very low values for estimated pressure drop.

At Production Stage 1, the type of heat exchanger is plate heat exchanger with capacity of 320 KW.

	Hot Stream		**Cold Stream**	
Fluid name:	Water		Propylene Glycol	
	In	**Out**	**In**	**Out**
Mass Flow Rate (Kg/s)	1		24.5	
Temperature (^{o}C)	20	10	-5	5
Operating Pressure - absolute (bar)	1		4	
Estimated Pressure Drop (bar)	0.1		0.4	
Allowable Pressure Drop (bar)	0.1		0.4	
Composition (%)	0.7		0.3	

Table 4: Input Data for Aspen Plus – Production Stage 1

At Production Stage 2, the type of heat exchanger is again plate heat exchanger with capacity of 160 KW.

	Hot Stream		**Cold Stream**	
Fluid name:	Water		Propylene Glycol	
	In	**Out**	**In**	**Out**
Mass Flow Rate (Kg/s)	1		11.5	
Temperature (^{o}C)	20	10	-5	5
Operating Pressure - absolute (bar)	1		4	
Estimated Pressure Drop (bar)	0.1		0.4	
Allowable Pressure Drop (bar)	0.1		0.4	
Composition (%)	0.7		0.3	

Table 5: Input Data for Aspen Plus – Production Stage 2

At Production Stage 4, the type of heat exchanger is plate heat exchanger too, with capacity of 352 KW.

	Hot Stream		**Cold Stream**	
Fluid name:	Water		Propylene Glycol	
	In	**Out**	**In**	**Out**
Mass Flow Rate (Kg/s)	1		27.25	
Temperature (^oC)	20	10	-5	5
Operating Pressure - absolute (bar)	1		4	
Estimated Pressure Drop (bar)	0.1		0.4	
Allowable Pressure Drop (bar)	0.1		0.4	
Composition (%)	0.7		0.3	

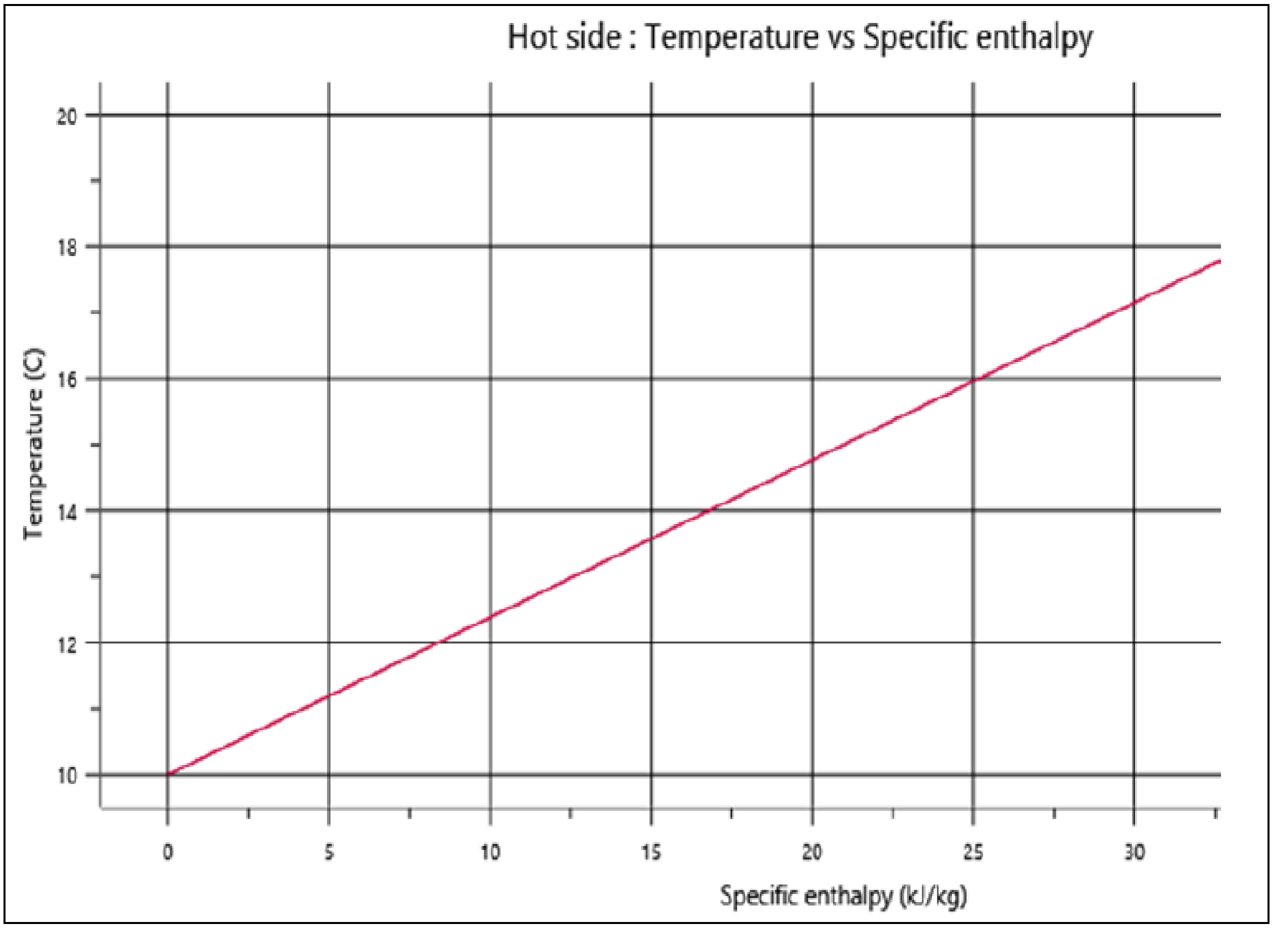
Table 6: Input Data for Aspen Plus – Production Stage 4

Automatically, Aspen Plus software generates the below values for thermodynamic properties in various temperatures based on the heat exchanger equipment details and provides also a chart for Temperature vs Specific Enthalpy for hot and cold stream, as shown below.

For water side:

Hot Stream			
Temperature (^oC)	10	15	20
Liquid Density (Kg/m^3)	998.8	999.02	998.83
Liquid Specific Heat (KJ/KgK)	4.198	4.195	4.194
Liquid Viscosity (mPa-s)	1.336	1.161	1.0163
Liquid Thermal Condition (W/m-K)	0.58	0.5869	0.5937
Liquid Surface Tension (N/m)	0.0742	0.0735	0.0728
Liquid molecular weight	18.00999	18.00999	18.00999
Specific Enthalpy (KJ/Kg)	0	21	42

Table 7: Output data from Aspen Plus – Water Side

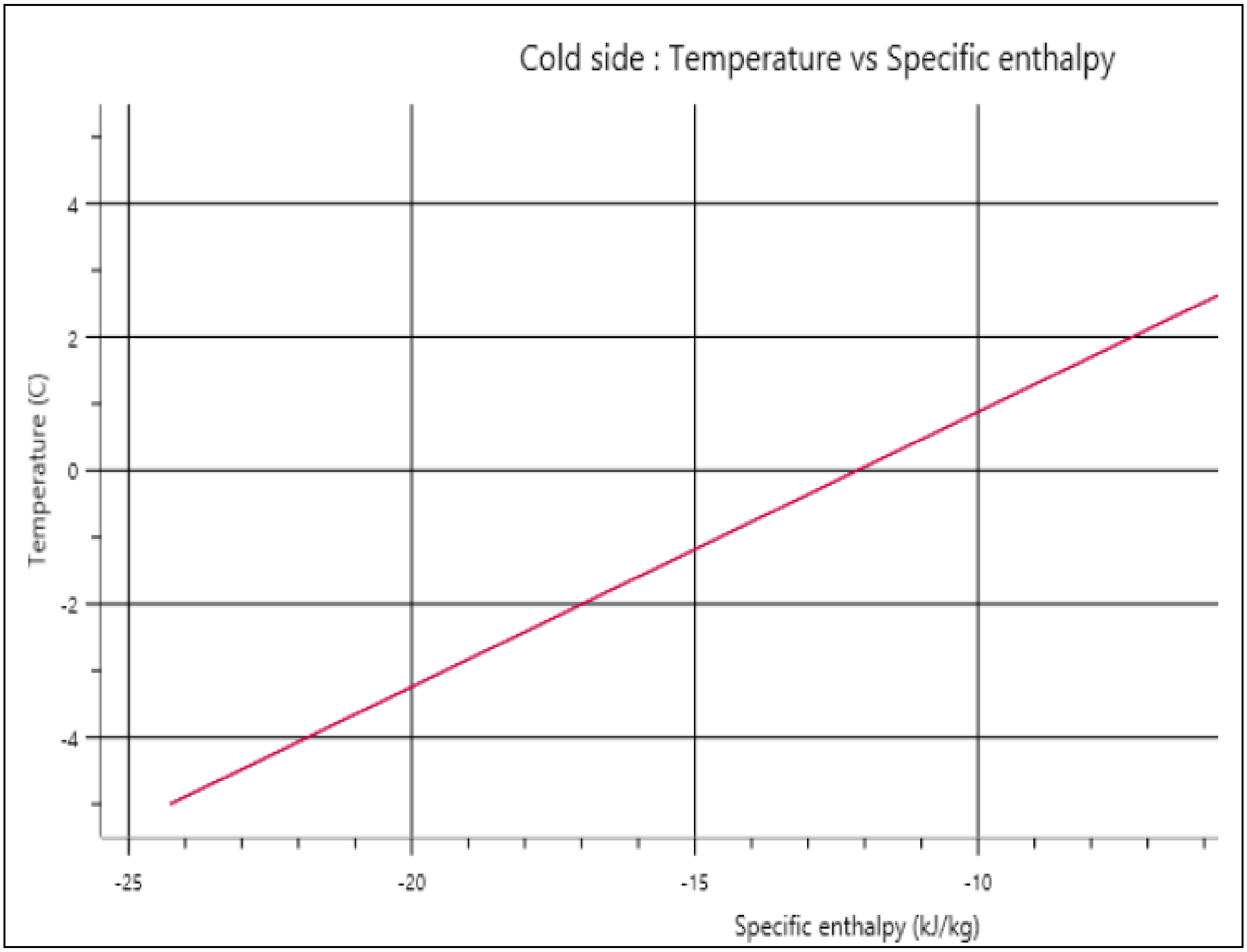


Picture 3: Temperature Vs Enthalpy chart – Water Side

For Propylene Glycol side:

Cold Stream			
Temperature (°C)	5	0	-5
Liquid Density (Kg/m³)	1044.77	1044.77	1044.77
Liquid Specific Heat (KJ/KgK)	2.427	2.427	2.427
Liquid Viscosity (mPa-s)	149.7443	197.3611	262.813
Liquid Thermal Condition (W/m-K)	0.2236	0.2236	0.2236
Liquid Surface Tension (N/m)	0.0379	0.0379	0.0379
Liquid molecular weight	76.09999	76.09999	76.09999
Specific Enthalpy (KJ/Kg)	0	-12.1	-24.3

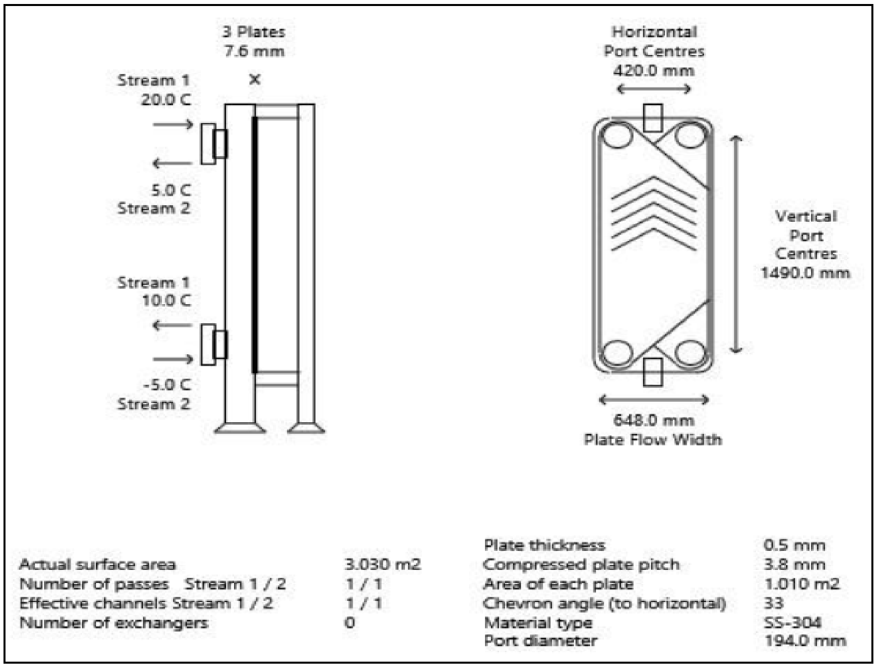
Table 8: Output data from Aspen Plus – Glycol Side



Picture 4: Temperature Vs Enthalpy chart – Glycol Side

Finally we get the heat exchanger simulation figures from the software for each 3 occasions, the three main consumers for Production Stages 1,2,4.

Occasion 1: For the Production Stage 1 where we have Total Heat Exchange equal to 320 KW, we get single number of fluid passes in each side and the actual surface area is round to 3030 m^2 according to Aspen Plus Database. In addition we get the metal plate thickness that is 0.5mm and also the surface area of each plate, the material of the plate Chevron angle (to horizontal) equal to 33^o.

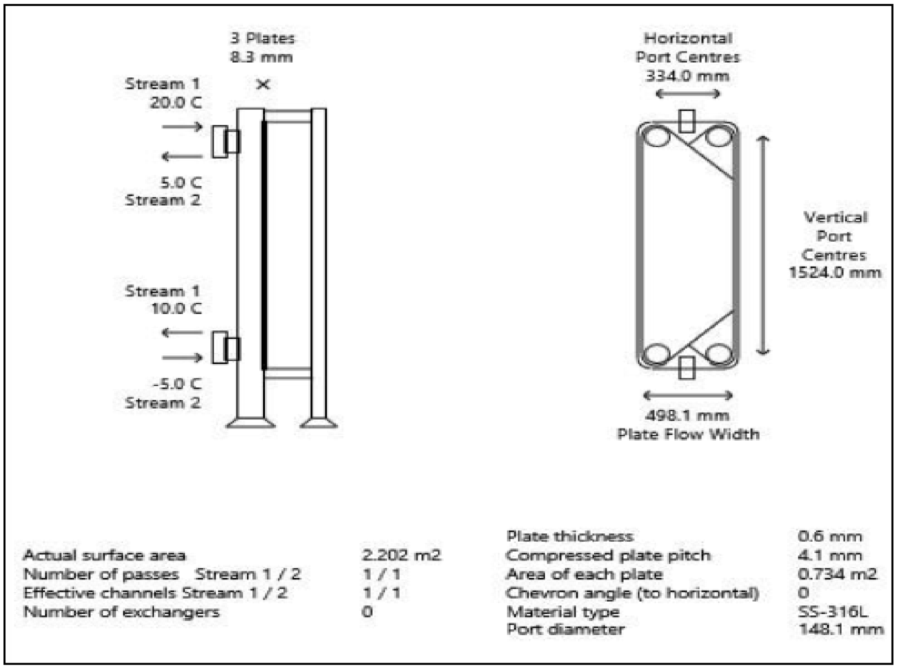


Actual surface area	3.030 m2
Number of passes Stream 1 / 2	1 / 1
Effective channels Stream 1 / 2	1 / 1
Number of exchangers	0

Plate thickness	0.5 mm
Compressed plate pitch	3.8 mm
Area of each plate	1.010 m2
Chevron angle (to horizontal)	33
Material type	SS-304
Port diameter	194.0 mm

Picture 5: Heat Exchanger Simulation – Production Stage 1

The second occasion refers to the Production Stage 2 with total Heat Exchange at 160 KW.



Actual surface area	2.202 m2
Number of passes Stream 1 / 2	1 / 1
Effective channels Stream 1 / 2	1 / 1
Number of exchangers	0

Plate thickness	0.6 mm
Compressed plate pitch	4.1 mm
Area of each plate	0.734 m2
Chevron angle (to horizontal)	0
Material type	SS-316L
Port diameter	148.1 mm

Picture 6: Heat Exchanger Simulation – Production Stage 2

The final occasion refers to the Production Stage 4 with total Heat Exchange at 352 KW which is the bigger consumer.

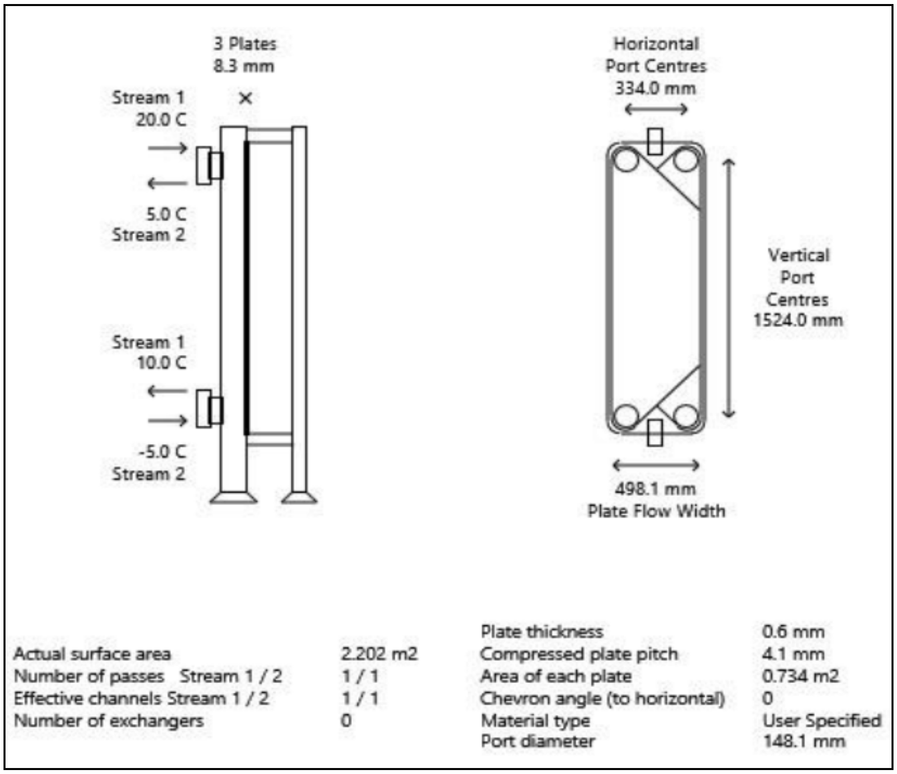


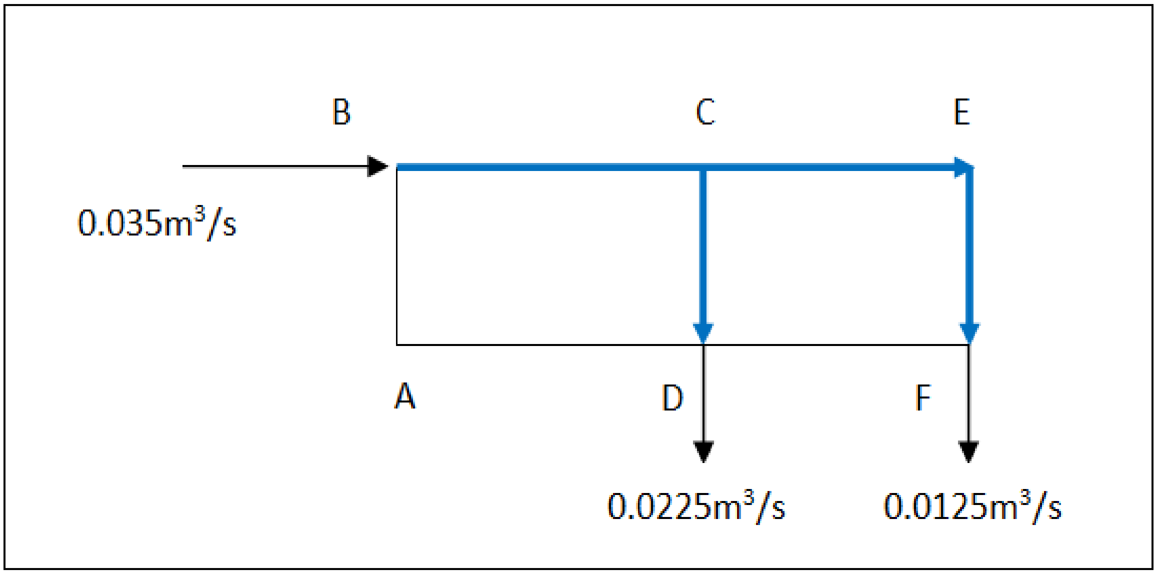
		Plate thickness	0.6 mm
Actual surface area	2.202 m2	Compressed plate pitch	4.1 mm
Number of passes Stream 1 / 2	1 / 1	Area of each plate	0.734 m2
Effective channels Stream 1 / 2	1 / 1	Chevron angle (to horizontal)	0
Number of exchangers	0	Material type	User Specified
		Port diameter	148.1 mm

Picture 7: Heat Exchanger Simulation – Production Stage 4

4.5 Flow Rates Calculations

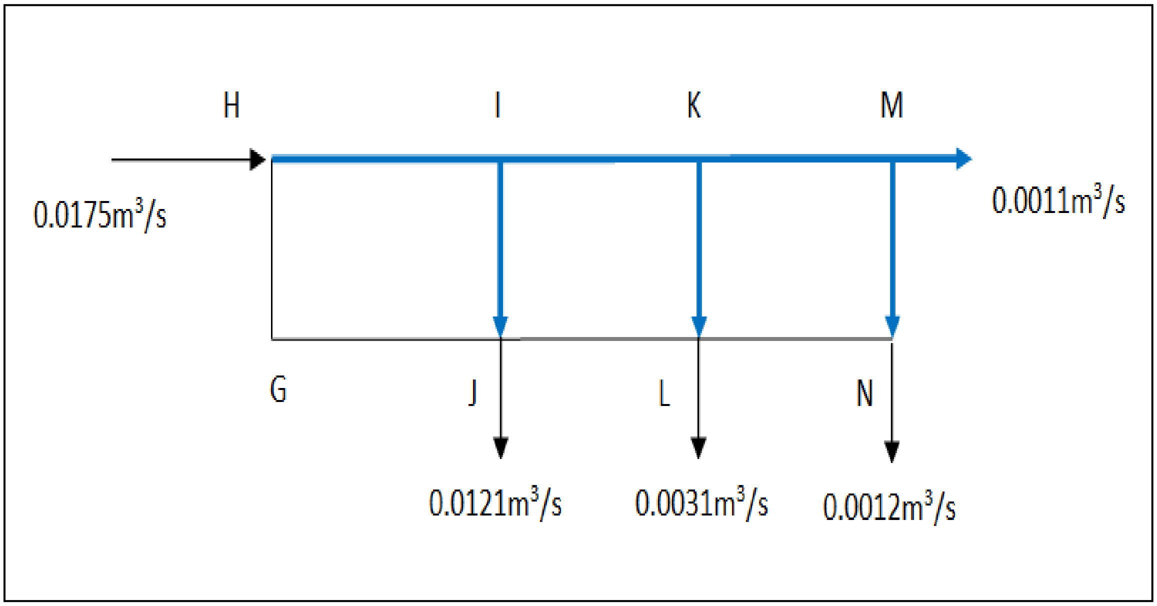
Taking into account the volume flow rate from supply pumping station at 250 m^3/h and also having the data for pipe dimensions, diameter and length at each branch we can calculate the flow rate at each sector and present the loop diagrams below.

Firstly, is presented the loop for Fermentation Tanks area. We have two lines that serve this tanks area and the first one is calculated at 0.0225 m³/s and second one at 0.0125 m³/s.



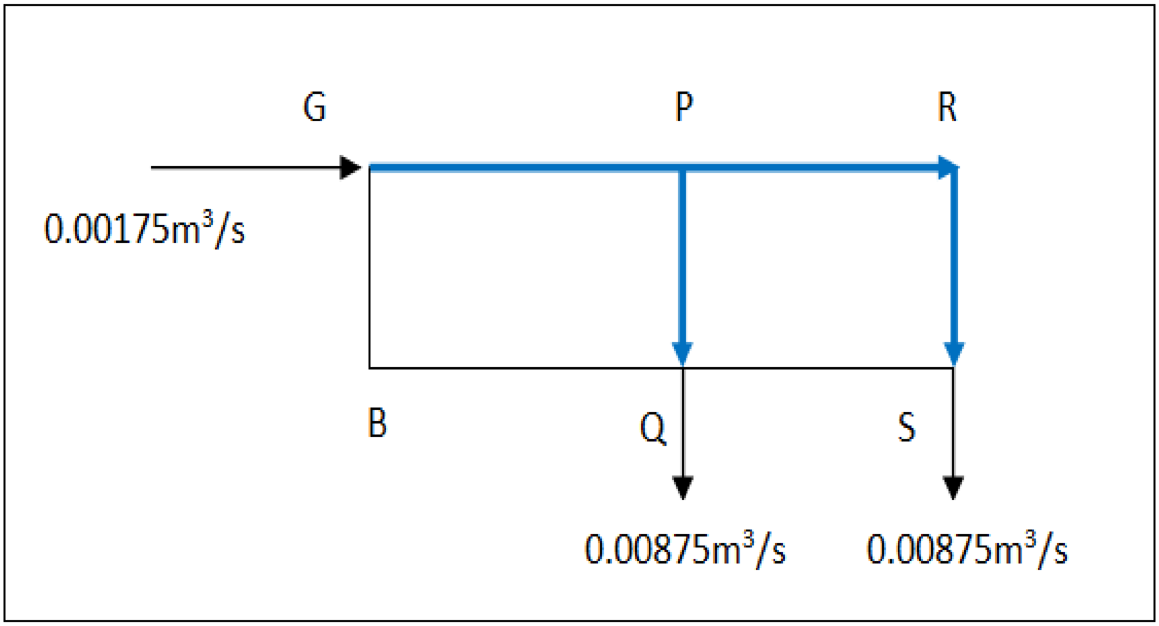
Picture 8: Fermentation Tanks - Flow rates

Second comes the loop for Processing Production area. This is the crucial area where the three main consumers exist. Inlet flow rate in this sector is only 0.0175 m³/s in order to cover more than the 70% of the demand.



Picture 9: Production Processing - Flow rates

Finally we have the loop for Storage Tanks and Production Packaging division, with the rest of 0.00175 m³/s.



Picture 10: Storage Tanks and Packaging - Flow rates

Chapter 5

Proposals – Solutions

From all the above it seems that cooling demand is much higher than the propylene-glycol system provides. Based on the calculated flow rates and comparing with the results from theoretical approach, there is a problem and more specific in the processing production branch loops of propylene-glycol. Because of this, lots of problems may rise affecting also production efficiency, product quality and operational cost. In order to mitigate capacity problem, engineering team can proceed to implement some solutions that will help refrigeration plant work in a better way.

5.1 Instruments installation for measurements

At first stage various instruments must be installed to have a clear view on what flows we get in each sector / branch. Non intrusive instruments can be installed with the ability not to cause plant shutdown or any delays on the production. In general such of instruments installation simplifies the compliance of safety and environmental aspects and reduce possible hazards for humans.

Proposed instruments installation presented below:

1. Temperature measuring devices / Thermometers

Picture 11: Thermometer Devices

Thermometers can be installed on the exterior surface of the metal pipe without any penetration need inside the pipe. Supporting methods of screws, clamps etc can be installed to ensure the proper position of the device. They have desired accuracy of measurement and respond time in temperature changes are under acceptable levels. Finally eliminates the risk of a thermo well failure.

2. Flow meter devices

Picture 12: Flow meter Devices

Ultrasonic flow meters are also non invasive device for flow monitoring of non-conductive fluids. It can be easily installed by clamping on the sensors.

There is a wide range of devices for measuring fluids in the pipes with dimensions from 12 to 7000mm diameter size, can measure without any problem depending process temperature (from -40 to 200 Celsius degrees.

5.2 Glycol Supply System - Adjustments

Second topic that may admit further adjustments is the glycol supply system. An observation is that the propylene-glycol supply pumps are operating at 70% of their capacity. In terms of flow rates, at maximum operation this amount reaches up to 250 m^3/h. If the set point is adjusted to 70%, that equals to 175 m^3/h, so the mass flow rate is even lower than we have calculated above.

For better operation maybe starting also the stand-by pump with another 125m3/h capacity at maximum speed is preferable to increase the mass flow rate. Pumps are settled in parallel installation set up and this will not affect any pressure increment in the lines. By doing this and have all the pumps running at 80% of their capacity, propylene-glycol circuit will increase by 40% the flow rate from existing situation.

That will cause some operational cost in electricity because of higher consumption coming from the pumps but on the other hand will decrease the rapid response of ammonia compressors at full operation capacity which means less operational cost, less water consumption, less breakdown times and malfunctions at refrigeration system.

5.3 Rescheduling Production Process

Third attempt is to adjust production line and especially in the beer processing line in order to decrease the cooling demand at the higher level from all stages at the same time. For example, at the 4th stage where there is a production of water with low oxygen concentration can be held and separated from other stages.

For example, when there is no production in progress, the deaeration water system can be started for production and save this water in an available beer storage tank until its usage. The storage tank has the ability to keep the temperature of the water in desired level and also has the ability to keep water quality in constant conditions without any contamination risk.

Some minor adjustments in product pipeline must be done to have the ability bypassing the normal process queue. By doing this, propylene-glycol system will gain the ability to serve other 'consumers' with a better efficiency. Removing the 352KW of cooling demand from the equation, that means that rest heat exchangers of the beer processing production line will handle to give necessary cool to the product without any delays in the production because of high temperatures.

Of course it is better to run all the systems at the same time for better efficiency, but because the refrigeration system is running 24/7 for providing cooling for fermentation and storage tanks then the factory will not have massive increase of energy consumption.

5.4 Upgrade Propylene-Glycol System

Another topic to discuss for improvement is the secondary cooling system its self. After calculating the 3 main consumers - heat exchangers of beer processing cooling load, it is obvious that cooling capacity of the system is lower than the demand. Ammonia refrigeration plant has the ability to provide up to 1400KW of cooling capacity. On the other side maximum capacity of ammonia / propylene-glycol heat exchanger is up to 1200KW. By adding further plates (approximately round to 40pcs) on the heat exchanger, easily can be achieved an upgrade of the complete system to 1400KW on both sides, ammonia and propylene-glycol.

It is an investment that costs, in terms of buying the plates, arrange at least 3-4 days without any production (can be easily arranged during winter period where beer consumption is much lower compared with summer period) in order to pump down ammonia system in that area and also recover ammonia and glycol quantities from emptying the heat exchanger, but it is worth to do this because factory now is running above the limits, it is an opportunity to do a maintenance cleaning of the heat exchanger from oil 'residues' on ammonia side and dirties removal on propylene-glycol side and give the opportunity to factory to think about future needs of the cooling system in terms of further production upgrades.

Moreover there is a potential to improve the balancing of the propylene-glycol system by adding a bigger or an additional glycol buffer tank between main heat exchanger and glycol pumps. By doing this we will achieve higher temperature 'storage' of the glycol which can be easily achieved during refrigeration system operation when there are no high cooling demands.

5.5 Renewable Energy Sources

Based on the electricity consumption that a refrigeration system needs to operate and create and cover necessary cooling load, there are alternative solutions and technologies to achieve that further than conventional ones. Also a combination of both systems can operate with more efficiency in terms of energy consumption and greenhouse emissions.

- Absorption refrigeration system with solar thermal panels: By installing such system the factory can achieve very high efficiency in general and especially in summer period, average coefficient performance (COP) can reach values below than 0.8.

- Photovoltaic panels (PVs) for electricity production: Installation of these panels at the range of 100 KWp, can produce energy up to 1300KWh per square meter which means that covers a significant percentage of annual demand of electricity. Especially during summer period when refrigeration's plant demand is at the higher level, then this system is an ultimate solution for reducing energy electricity purchases from national grid and also reduce CO_2 emissions.

Both solutions needs a significant capital amount for their implementation, but for a healthy company that moves forward and take into consideration all guidelines from national and European councils for reducing energy consumption and greenhouse gasses emissions then is one-way path. Especially for the PVs where the payback period is very short and investment risk is very low, there is a potential for installing.

Chapter 6

Conclusions

Changes of environmental and weather conditions and abuse or recklessness of energy waste without any limitations that happen nowadays through the highly consumption from energy intensive facilities, forced to a new approach of management on energy sources we have.

There are a lot of opportunities for improvements when we are dealing with very high operational costs and high energy consumptions.

At this case small steps for improvement can cause energy needs reduction and increase production efficiency and when we are referring a brewery factory that demand on any field are very high especially on electricity, water, fuel and waste water treatment, then every attempt for energy savings are very valuable.

Everybody, from companies owners to government officers and in general stakeholders in energy management need to run any case study to identify possible solutions for saving energy because we need to push on any field in order to achieve carbon neutralization. Zero-carbon refrigeration technologies are very significant assets for a sustainable energy operation and natural refrigeration systems will be prominent for the near future and will contribute to the effort for low emissions processes.

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