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Appendix

Introduction and Background Information

Industrial refrigeration systems each accomplish their task with unique designs; nonetheless, all refrigeration plants use similar components and processes. During normal refrigeration operation, sub-cooled liquid refrigerant is routed from a compressor through evaporator coils. As low-pressure refrigerant (in this case anhydrous ammonia) enters the evaporator, heat is absorbed from the ambient air in the refrigerated space, causing it to evaporate. This causes an evaporative cooling effect. Vapor from this process is recompressed and sent to a condenser to produce more liquid for use in refrigeration in the network of evaporators. Figure 1, shown below, is a simple diagram showing the flow of ammonia through a normal refrigeration cycle. It should be noted that the arrow on the right side of Figure 1 represents the heat from the ambient air being absorbed by the liquid ammonia, and the arrow on the left side of Figure 1 represents the heat held in the ammonia vapor being removed using a condenser (located outside the refrigerated space).

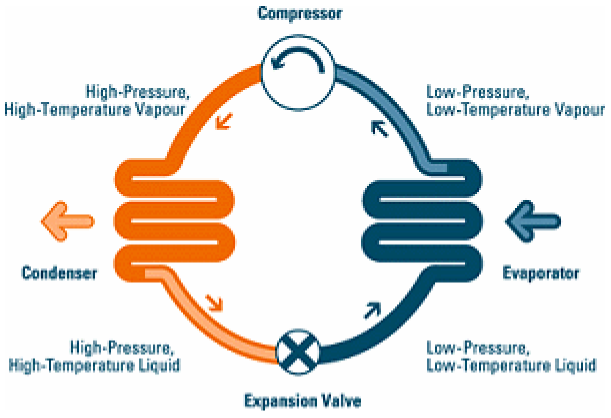

Figure 1-The refrigeration cycle

This process has a critical inherent flaw. Any moisture content, which has infiltrated the cold space, either from load (fresh produce or other items releasing moisture), or from traffic into and out of the space will tend to freeze to the coldest point in the space. The evaporator coils are the coldest point in refrigeration systems, so they become coated with frost. A critical quantity of frost inhibits effective heat transfer from the cold space. This problem has been recognized as a possible source for energy savings for refrigeration companies.

Industrial refrigeration systems address the problem of frost build-up using a frost removal process known as hot gas defrost. In this process, one evaporator in a refrigerated space will be targeted for defrost at a fixed time interval (every 24 hours for example). This evaporator no longer receives liquid refrigerant from the system, and the evaporator is allowed to evacuate. Then high pressure, superheated ammonia vapor refrigerant is forced through the evaporator coils. This process effectively turns the evaporator coils into a condenser. When the ammonia vapor or “hot gas”, is sent through the evaporator coils it condenses and gives off its latent heat to the frost surrounding the coils and melts the frost. This hot gas is sent through the coils for a preset amount of time, and then the defrost cycle is terminated. Next, the coil pressure is allowed to bleed off, and then the sub-cooled liquid refrigerant is allowed to resume its normal flow.

Figure 2 shows the flow of hot gas through an evaporator. The components shown in Figure 2 are intended to represent the most common design of an evaporator. It should be noted that the evaporators used in the Portland State University Hot Gas Defrost Senior Design Team (PSUHGDSDT) study do not normally have inlet and outlet pressure regulators, flow regulator, or a liquid drainer (commonly known as a float drainer).

The defrost cycle shown in Figure 2 begins with the supply of liquid refrigerant being terminated by closing the liquid supply solenoid valve. After all of the liquid refrigerant has been evacuated from the evaporator, the flow of hot gas is initiated through the drain pan, which is done to keep any melt water from evaporator coils from freezing when it is collected in the pan. Next, the gas is routed through the evaporator to melt off any frost build up. Then, at the exit of the evaporator a mixture of ammonia gas and liquid is sent to suction for processing (recompressing—in the case of gas), or for use in the refrigeration cycle.

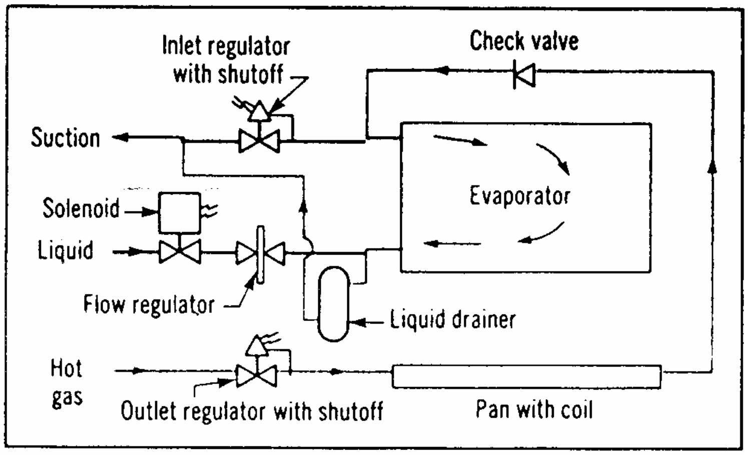

Figure 2-The hot gas defrost cycle

In industry today some control schemes exist for insuring more efficient defrost cycles. Choosing the proper defrost duration and parameters such as inlet and suction pressure can dramatically improve defrost efficiencies. Different valve schemes and float-drainers can be used to offer control over defrost parameters. In addition, simple measures such as installing a frost sensor, or a temperature probe at the exit of the evaporator can be used to determine when defrosts should be initiated, and subsequently terminated.

The refrigeration process has been the source of many studies, and much is known regarding this process, and the thermodynamic states required to refrigerate a space efficiently. In contrast, the hot gas defrost process has been the source of rule-of-thumb engineering. Much of the heat transfer modeling of this process is difficult, approximate, or impossible. Also, most refrigeration systems have their own unique design, which makes creating heat transfer models difficult. As a result, little is known about the most efficient method to conduct a hot gas defrost. This is a great opportunity for energy savings for refrigerated spaces.

It is clear that designing a system which could measure the most significant defrost parameters in a way that could be applied to any refrigerated space is needed. In accordance with this need the Portland State University Hot Gas Defrost Senior Design Team (PSUHGDSDT) has teamed with Cascade Energy Engineering (CEE) to design a system that can accurately and effectively measure the thermodynamic properties relevant to the hot gas defrost cycle.

Mission Statement

The mission of the Portland State University Hot Gas Defrost Senior Design Team (PSUHGDSDT) is to design and fabricate a system which can effectively measure multiphase thermodynamic properties necessary to determine the efficiency of the hot gas defrost cycle. In accordance with this mission, the PSUHGDSDT will design and fabricate a piping and measurement system in order to develop methods that can be used for minimally invasive measurement of the hot gas defrost cycle.

Timeline

During the fall, winter and spring terms the PSUHGDSDT has followed a timeline that was conceived of by the team. The timeline is attached at Appendix 6.

Brief Overview of the Design Process

To insure a comprehensive understanding and evaluation of the requirements and potential design solutions the PSUHGDSDT created the Product Design Specification (PDS), conducted external and internal searches, and a final concept evaluation to select the final design.

Product Design Specifications Summary

The PDS is a list of the important characteristics of the end product. For our project the most important PDS are: cost, accuracy, simplicity and the ability of the design to yield a complete solution to the PDS requirements. The final PDS document is included as Appendix 1.

External Search Summary

Through the external search the team was unable to find any products or services that addressed this project in its entirety. If such a system exists, it would be proprietary. Through this search the team found many products that would be applicable on the sub-component level. Though no product was found that could yield the necessary fluid quality data. The external search document is included as Appendix 2.

Internal Search Summary

All of the designs that were generated can be classified as direct or indirect. This classification refers to how the quality of the fluid exiting the evaporator coil is determined. The ‘direct designs’ directly measures the quality, where the ‘indirect designs’ solve an energy balance to determine the quality. The internal search document is located as Appendix 3. The top-level concepts are evaluated in the next section.

Concept Evaluation Summary

For the concept evaluation the team used a decision matrix approach, criteria were compiled through PDS, and other important issues. The three designs evaluated are numbered #1, #2, and #3. These designs are, respectively: hanging tare weight—where the change in the mass of the evaporator is measured to show when to start and stop the defrost; using a two-phase flow meter—which would give the necessary quality data at the exit; and a flow separator installed at the exit of the coil to measure the mass flow rate of the exiting fluid. Design #1 and #2 were rejected due to the low values on the “screening matrix”. Design #3, the flow separator, met the most criteria and became the final design. The concept evaluation document can be found in its entirety as Appendix 4.

Determination of Useful Energy

To determine the efficiency of the hot gas defrost cycle it is necessary to first define useful energy input by the hot gas during the defrost process. For the purposes of this project useful energy has been defined as the energy that goes to melting the frost off the evaporator coil and removing it from the refrigerated space. The energy that is expended to perform a defrost is dissipated in many ways that are not considered useful, these include: radiation, natural convection, sensible heating of the evaporator equipment, and sublimated frost that stays in the cold space atmosphere. The last item is considered an inefficiency because even though frost is removed from the coil, it returns to the cold space to become a load on the system in the form of future frost on the evaporator coils in the space. An energy balance can be created that equates the energy put into the defrost process to the useful work done and the effects of the inefficiencies.

The energy balance equation is defined as:

(1) $Q_{process} = Q_{melt} + Q_{sublimation} + Q_{sensible,\ evaporator} + Q_{radiation} + Q_{convection} + Q_{sensible,\ ice}$

Efficiency is defined as:

(2) $\eta = Q_{melt} / Q_{process}$

The left hand side of the energy balance equation represents the total amount of energy supplied to the process by the hot gas. In order to determine the energy supplied by the hot gas it is necessary to determine the change in enthalpy experienced by the refrigerant. The determination of the enthalpy of the refrigerant at the entrance to the evaporator requires that temperature and pressure be known. The gas is in a superheated state, the thermodynamic state of the refrigerant can be determined with these two values. To determine the total amount of energy supplied it is also necessary to know the amount of mass that passed through the system. At the exit of the evaporator coil the refrigerant is in a saturated state, a portion of the hot gas having given off its latent heat and condensed to liquid refrigerant, the remainder of the refrigerant remaining in a gaseous state. To determine the enthalpy of the refrigerant in a saturated state the quality must be known, as well as the temperature and pressure. To see a complete energy balance see Appendix 13.

Determining the useful energy input into the defrost process required the use of a calibrated melt water collection vessel. The melted frost from each defrost was collected in the vessel, and the volume of melt water recorded, and converted to total mass of melt water. Since the melt water is sub-cooled liquid at atmospheric pressure only temperature measurement was needed to determine its enthalpy. The melt water temperature was measured in the drain pan, to avoid the fluid absorbing heat from heated piping, or the outdoor air.

Detailed Design

Separated flow design

The changing state of the ammonia refrigerant during the hot gas defrost (HGD) process poses many problems when trying to develop a way to measure the variables related to hot gas defrost. One such challenge is posed when considering how to measure the respective mass flow rates of the condensed defrost gas (liquid) and the uncondensed defrost gas. Through our research[1] and experience, we determined that there is what is known as "bubbly" flow. This means that the non-condensed refrigerant is present in the form of bubbles found in the condensed refrigerant.

In order to measure the needed mass flow rates under the given conditions at the exit of the evaporator during defrost, we found it necessary to devise a means of separating the two phases of refrigerant found here, so that they could be measured individually.

To achieve this goal, the team has designed, fabricated, installed, tested, calibrated and operated a flow separator (see Figure 3), the many design considerations are described in Appendix 10. There are two exits from this section of pipe, separated by a baffle. The first exit is at the topside of the tank. It allows the non-condensed refrigerant vapor to pass through a flow meter and backpressure regulator before dropping back to the low-pressure suction side of the system. The second exit of the separation vessel exits from the bottom

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[1] Interview with Ward Ristau, P.E., Permacold Engineering, Jan 2003

side of the vessel. Here the liquid refrigerant is forced through a float drainer, which doesn't allow gas past, by the pressure that is present in the coil during defrost. The presence of these two exits serves a two-fold purpose. First, it allows the amount of uncondensed refrigerant exiting the coil through a metering device to be measured. Second, it allows the evaporator to be defrosted under multiple modes of defrost such as: float drainer alone, float drainer and outlet regulator, back pressure regulator alone, or any other metering device for defrost. This is of great value to our customers; since they are interested in determining the best defrost practices possible with hot gas defrost. We were able to investigate all modes of hot gas defrost that are currently practiced in the industry. Figure 4 shows the completed fabricated flow separator, for further diagrams of the system see Appendix 5.

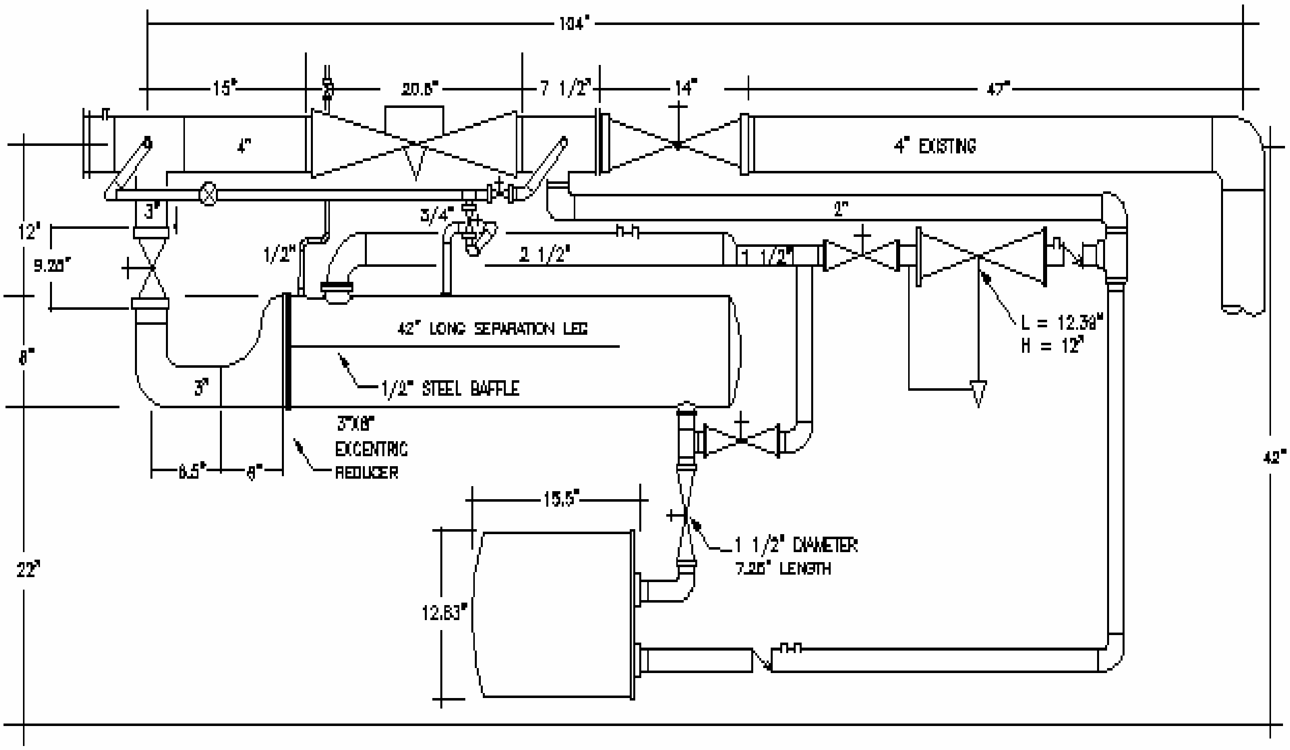

Figure 3-Flow separator detail with dimensions

Figure 4--Separator Fabrication

Heated enclosure

A heated enclosure was designed to: maintain an internal environment (temperature, relative humidity) conducive to the safe operation of the data logging equipment; employ some means of stable mounting for individual data loggers and other equipment; be powered by a standard 120V outlet or an internal battery; be securely mounted in a convenient emplacement in the cold space; include safety features to avoid overheating of equipment.

The heated enclosure contains a heater controlled by a thermostat, lights, electrical outlets, a shelf for a laptop, and a back wall covered in Velcro for the data loggers to attach to. The box was fabricated out of sheet metal, with hinges, handles, and removable legs. To ensure that the electrical equipment stayed at the right temperature, a human sized gaiter was designed and sewed. The gaiter slips over the box, and allows a person to climb inside to work without letting heat escape. The heated enclosure can be seen in Figure 5.

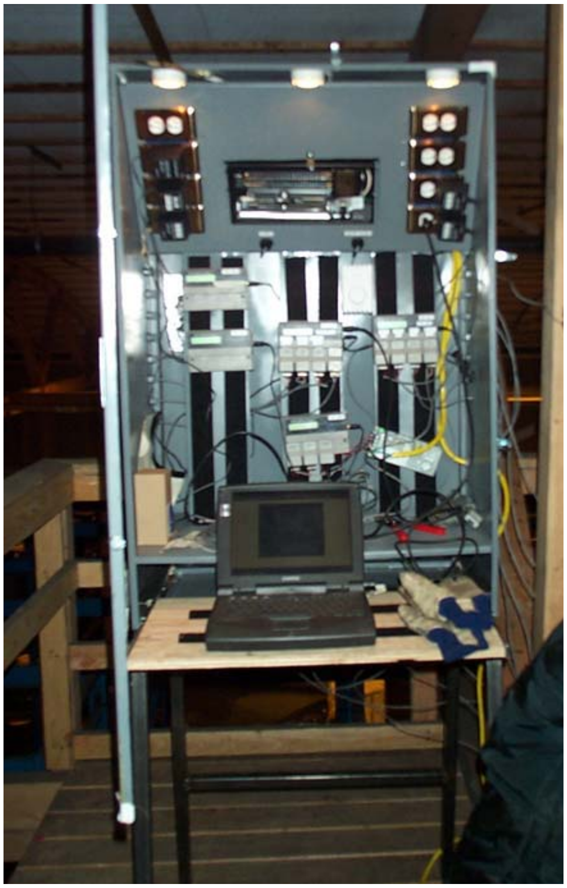

Figure 5--Heated enclosure installed (Gaiter removed for repairs)

Data collection methods

At the beginning of each defrost each data logger was set to the defrost start time. During the defrost signals were sent from each sensor to the heated enclosure and the data loggers inside. Signals were received as either 4-20 mA signals for flow and temperature measurement, or 5-volt signals for the pressure transducers. These signals were sampled every 3 seconds, and converted to the desired units.

Observations were recorded during each defrost including:

- Sight glass liquid vs. gas levels
- Sublimation
- Time when all frost removed from coils and fins
- Melt water volume with respect to time

Finally, each data set was downloaded to a laptop, and imported to Microsoft Excel, where enthalpies and defrost efficiencies would be calculated.

Analysis

A key quantity to our analysis is the enthalpy of the ammonia refrigerant at various points in the system. This quantity refers the to the heat content of the fluid; examination of the change in enthalpy between the supply and return at the coil is a clear indication of how much heat was removed from the refrigerant during the process. Appendix 12 shows the spreadsheets that were used to carry out the calculations that were developed out of the following analysis as well as the collected data. This spreadsheet has been paired down to show only the data points that were actually used for the calculations.

The enthalpy (h) is a function of temperature (T) and pressure (P).

$$h(T,P)$$

In the case where the fluid is saturated, either the temperature or the pressure alone may determine the enthalpy. Proprietary Visual Basic functions were used to calculate the enthalpy of saturated refrigerant liquid and vapor at different points in our analysis. These values could also be obtained from standard ammonia properties tables. Enthalpies of superheated refrigerant were read from a standard ammonia superheat table. .

The change in the heat content of the refrigerant as it flowed through the evaporator during defrost was found as a function of the respective enthalpies and mass flow rates of the hot gas supply, suction vapor return, and suction liquid return as follows.

$$\begin{aligned}\text{Change in Heat Content} &= \Delta Q(\Delta m_{hgs}, h_{hgs}, \Delta m_{return\_vapor}, h_{return\_vapor}, \Delta m_{return\_liquid}, h_{return\_liquid}) \\ &= (\Delta m * h)_{hot\_gas} - \left((\Delta m * h)_{return\_vapor} + (\Delta m * h)_{return\_liquid}\right)\end{aligned}$$

The energy used during each time step (corresponding to the data collection interval) during process can be determined by taking the summation of this change in heat content for each time step multiplied by change in time over each interval.

$$\Delta \mathrm{E}_{used} = \sum_{i}^{n} \Delta Q * \Delta t$$

Taking the summation of the change in the energy state of the refrigerant at each time step over the duration of the defrost yields the total energy that went to the defrost. Recall from the energy balance that this quantity includes the useful energy as well as the wasted energy.

$$\mathrm{E}_{total} = \sum_{i}^{n} \Delta \mathrm{E}$$

The useful energy was defined as the energy that went towards melting the frost and removing the resulting melt from the space. To accomplish this, the frost must first be heated to the melting temperature. At this point in the process, the energy can go towards changing the phase of the frost to liquid (in the meantime some of the frost and melt water is going to sublimation and evaporation respectively). The draining water must be slightly heated to avoid re-freezing in the drain pan. To summarize, the frost must be sensibly heated to the melting temperature, the heat of fusion is added to the frost to melt it, and the resulting melt water is heated to avoid re-freezing in the cold environment.

The quantities important to determining the useful energy associated with this process were obtained by taking measurements of the volume of the melt, the initial temperature of the frost, and the temperature of the melt water. The melt water temperature was taken in the drain pan of the coil at each time step. To obtain an estimate of the average temperature of the melt water exiting the refrigerated space, a simple average of the logged temperature readings was calculated in the spreadsheet. Energy ($\mathrm{E}_{\mathrm{defrost}}$) used to melt the ice off the coil is found using the specific heat of ice ($\mathrm{C}_{\mathrm{p\_ice}}$) and water ($\mathrm{C}_{\mathrm{p\_water}}$), multiplied by the temperature change during those processes and the latent heat of fusion, this is all multiplied by the mass of the melt water ($\mathrm{M}_{\mathrm{melt}}$) as follows.

$$\mathrm{E}_{defrost} = \mathrm{M}_{melt}[(T_{freezing\_water} - T_{initial}) * C_{p\_ice} + (T_{average\_melt\_water} - \mathrm{T}_{freezing}) * C_{p\_water} + l_f]$$

The heat efficiency of the process is found by dividing the useful energy, $\mathrm{E}_{\mathrm{defrost}}$ by the total, energy, $\mathrm{E}_{\mathrm{total}}$.

$$\eta = \frac{E_{defrost}}{E_{total}}$$

Table 1 summarizes the quantities obtained by applying the analysis described on the previous pages to the logged data. Three different types of defrost were conducted. The first method was an unregulated defrost as is practiced currently at the plant where the study was conducted. In this type of defrost the refrigerant flow returning to suction during defrost is passed through a statically adjusted hand expansion valve. The next type of defrost was a back pressure regulated one. This is similar to the first type of defrost in that the gas entering the coil is unregulated, while there is an attempt to regulated the pressure at the exit of the coil. The difference is that instead of using a statically adjusted valve, a regulator will modulating capabilities is used to hold the exit pressure at a specific set point. In the last defrost variation, an outlet regulator (at the entrance of the coil) is coupled with a float drainer at the exit that will only allow liquid to pass. This would seem to be the most desirable form of defrost in that it does not allow any uncondensed gas to return to suction as well as maintaining a specific pressure at the entrance of the coil to avoid excessive heating that can cause sublimation.

It should be noted that, though the back pressure regulated defrost appears to have the greatest heat efficiency, this defrost allowed the greatest amount of defrost gases to return to suction (~70% at steady state). This indicates the need to further study the effects of defrost on compressor work.

Table 1- Calculated efficiencies for different defrost conditions

	Melt Water Weight	**Energy to Defrost**	**Energy Used**	**Defrost Efficiency**
Defrost Method	**(lb)**	**(Btu)**	**(Btu)**	**(%)**
Unregulated	**184**	**34 391**	**391 543**	**8.8%**
Back Pressure Regulated	**376**	**67 788**	**317 967**	**21.3%**
Outlet Reg/ Float Drainer	**328**	**55 595**	**450 383**	**12.3%**

Figure 6 shows an important finding that was obtained during the course of our analysis activities. This is a plot of the temperature profile of the melt water in the drain pan of the coil during a typical defrost. The different stages of the defrost have been labeled according to the visual observations that were made during the defrost.

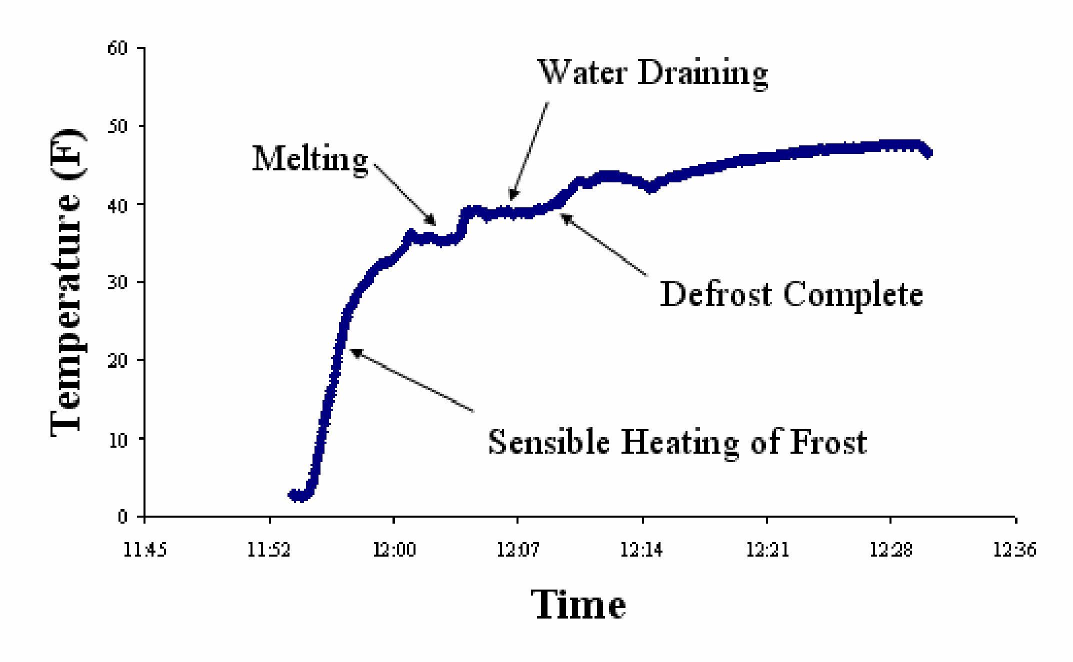

Figure 6- The stages of a hot gas defrost as noted using a plot of melt water temperature

The first section of Figure 6 corresponds the sensible heating of the frost. Note that this process takes place rapidly due to the relatively small amount of energy associated with sensible heating. Another important reason for this rapid heating is that the temperature difference between the frost and the hot gas is highest in the early stages of the defrost, this facilitates rapid heat transfer between the frost and the fluid passing through the coil.

The next region labeled on Figure 6 is the actual melting of the frost. The temperature during this phase is quasi-steady at a level just above the freezing point. This is likely due to the persistent presence of frost that keeps the melt water temperature from rising significantly as it passes along the fins of the coil and out the drain pan.

Once all of the frost has been removed from the fins, large quantities of melt water are still present in the drain pan of the coil. Due to slow draining of the coil, the water appears to heat up from the pan heaters, which are being heated by the hot gas as well. The temperature of the water seems to temporarily reach a steady state condition until the pan is completely emptied, at which time the defrost is effectively complete. A steady rise in the pan temperature then occurs due to the absence of water in the coil to keep its temperature down.

Melt water temperature plots can be used to identify the point at which the defrost was completed. This coupled with the measurements of mass flow to the coil as well as temperature and pressure will allow an energy efficiency engineer to carry out calculations that translate this flow rate into compressor work, from which a kWh potential savings can be obtained.

One problem that the team faced was that the flow meters were calibrated to read two and half times what the evaporator coil manufacturer specified to the be the maximum flow rate, though for each defrost the flow meters were "pegged out". This is gone into at length in the Findings section of this paper. The flow rate calculations can be found in Appendix 9.

Uncertainty Analysis

The certainty of our results depends upon the precision of our instruments, as well as our calibration of them. The instrumentation used in this project includes: flow meters, pressure transducers, wetted RTD temperature sensors, and surface mounted thermistor temperature sensors. The flow meters have a National Institute of Standards and Technology traceable calibration performed at the factory. The temperature sensors are tested for correct output in an ice bath, and crosschecked for agreement at other temperatures. The pressure sensors are checked for proper zero at ambient pressure. With all reasonable steps taken to assure that the instrumentation is calibrated, the precision of the instruments still introduce a certain amount of uncertainty. The analysis in Appendix 11 shows the approach taken to compute the overall uncertainty in our separator design, which is 3.1%. The results of the analysis show that nearly all of the uncertainty in the energy consumed during the defrost is the result of flow meter uncertainty. The effect of uncertainty in the temperatures and pressures has very little effect on the enthalpy of the ammonia. The uncertainty in the flow meters was responsible for most of the overall uncertainty. The mass of ammonia that is unaccounted for represents a large amount of energy because of the possibility that it had changed states, releasing its latent heat.

In addition to the uncertainty in the separator instrumentation, there is uncertainty in the mass of melt water collected during a defrost cycle. The melt water in this project is collected in a graduated, calibrated barrel. The mass of the melt water is then calculated from the volume collected. The melt water collection barrel was graduated and calibrated by using a large graduated cylinder, which was rated at 5% error.

Cost

In the PDS document it was specified that the cost of the solution would be less than \$5000. It is important to separate the cost of the solution that is to be recommended from the cost of the study itself. The minimally invasive system outlined in the recommendation section will meet the PDS goal easily and should have a cost of around \$3000. The cost of performing the fully invasive study was \$16,500. The team was able to acquire many of the parts, such as the valves, for free from vendors interested in being a part of this project. Other hardware such the flow meters and the temperature sensors were acquired at a discounted price. The cost of the project without the donations, discounts and donated consulting is calculated to be nearly \$36,000. For a detailed breakdown of the costs incurred during this project see Appendix 8. Appendix 7 includes much of the written correspondence that took place while attempting to secure discounted costs for the many necessary items.

Verification

Verification of the design consisted of several methods including visual, direct comparison, and operation. In order to verify proper operation of the flow separator design, it was necessary to install sight glasses in strategic locations. During each defrost data collection, each sight glass would be repeatedly inspected, and the phase of the flow recorded.

One sight glass was located at the separator entrance. This sight glass was installed to visually verify what phase the ammonia was in as it exited the evaporator coils. Ideally, only pure liquid would exit the evaporator during a defrost. This avoids sending gas back to the compressor (false loading). Close inspection of Figure 7 reveals both liquid (the dark region in the bottom of the sight glass) and gas phases present at the exit of the evaporator coil.

The second sight glass was installed in the hot gas supply line. This sight glass, shown in Figure 8, was installed to verify whether liquid slugs collect in the hot gas header between defrosts. The reflection of only light in Figure 8 indicates the presence of only gas phase in the hot gas supply line at the time of the photograph being taken. However, it could be visually noted that at the beginning of a defrost, liquid slugs were present in the hot gas supply line.

The third sight glass was located at the exit of the float drainer, as seen in Figure 9. The float drainer is designed to allow only liquid to pass, but it was expected that as the liquid passed from the exit of the evaporator (approximately 70 psi), to the exit of the float drain (suction pressure of approximately 15 psi) the pressure drop would cause the liquid to flash into gas phase. This expectation was confirmed by visual inspection of the sight glass in Figure 9. The dark portion on the bottom of the sight glass is clearly liquid phase, while the upper portion of the sight glass is filled with 'flash gas'. This flash gas is undesirable, since the return of any gas to the compressor is considered false loading.

The fourth sight glass, which can be seen in Figure 10, is located in the gas line off of the flow separator. This sight glass allowed for the visual verification that the flow separator was actually separating the flow into liquid and gas components. The light reflection in Figure 10 shows that there is only gas present in the gas line of the flow separator. This confirms that the device was properly separating flow.

Figure 7-Flow separator entrance sight glass

Figure 8-Hot gas supply sight glass

Figure 9-Float drainer exit sight glass

Figure 10-Flow separator gas return sight glass

The second mode of verification was the comparison of thermistor (surface) versus wetted thermal well temperature measurement. Figure 11 shows the difference between the two measurement methods. The difference between the two measurement methods is considered negligible, since the temperature measurement is used to determine enthalpy, which changes very little with a few degrees of temperature change.

The fact that surface and wetted temperature measurement can be used interchangeably, allows for the recommendation that thermistor temperature measurement could be used when only non-invasive measurement is possible. In addition, thermistor melt water temperature measurement has shown to be a good method of determining the needed duration of defrosts (see analysis section).

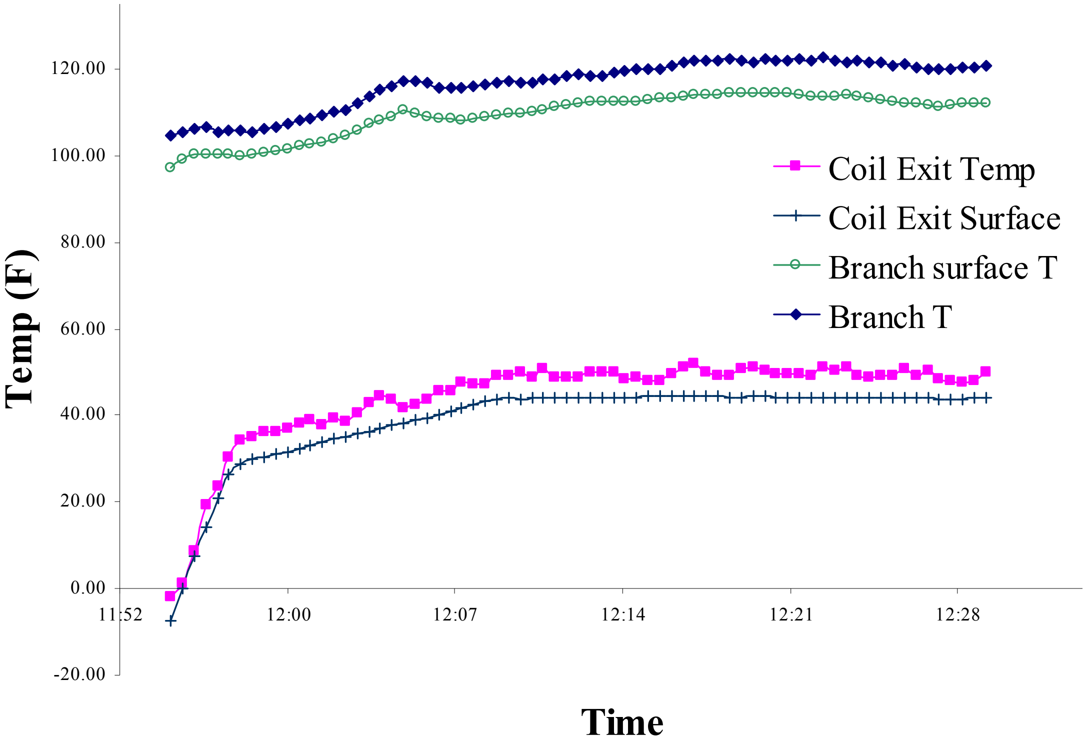

Figure 11-Thermistor versus RTD temperature measurement

The final method of verification is operation. Our flow separator provided the needed thermodynamic property measurements to determine the efficiency of the hot gas defrost cycle. In addition, the separator allowed for the recommendation of both non-invasive and minimally invasive measurement schemes to determine needed defrost duration, or wasted input energy, respectively. In addition, our heated enclosure proved capable of keeping our data logging equipment within their operating temperature range. The enclosure and gaiter provided enough warmth for the operator to use the laptop for initiating data collection, and downloading the data without the need for gloved hands. Long-term exposure of hands or any other part of the body simply would have made this project impossible.

Findings

Through our study of the defrost data and observations, the team has found some very interesting and unexpected characteristics of the cycle. Previous in this document there was reference to errors in the calibration of the flow meters. Through discussions with the evaporator coil manufacturer an expected mass flow rate was found to be 1000 lb/hr, and the flow meters were calibrated and set to output signal in the 0 to 2500-lb/hr range. For each of the six defrost that were preformed the mass flow rate exceeded the 2500 lb/hr mark at the beginning of each. The flow rate was transient in nature and within a few minutes decreased down to within the original 1000-lb/hr range.

This finding is a surprise to all interested parties; this shows that the manufactures, and system designer's models and methods are flawed. Their expectations did not correspond to the flow rates at the start of a defrost. It may be explained by the fact that the evaporator coil has the greatest heat transfer capacity right at the beginning of a defrost because the difference in the temperature of the frosted coils to the hot gas is the greatest. This would cause the hot gas to condense immediately and drop the pressure by creating a void—the compressor, which is feeding the process, has enough capacity to keep the pressure up to specification. Though it needs to pump quite a bit more gas to the evaporator to do this. That would explain why the flow rate is so high at the beginning and then drops off as the temperature of the coil increases.

Because the hot gas mass flow rate is directly related to the energy consumption of the compressor, this is a very important and interesting finding. Cascade Energy Engineering will investigate the initial transient condition further, as this could be an energy savings point that they could get moneys from utilities to investigate.

Recommendations

Our solution is in the form of recommendations that will be given to Cascade Energy Engineering. These recommendations are based on findings from the numerical data and visual observations recorded on each defrost. The two recommendations are organized as quantitative and qualitative.

The quantitative recommendation is to use minimally invasive instrumentation to measure mass flow, temperature and pressure to determine wasted energy input to the defrost cycle. The qualitative recommendation will use only a temperature measurement to determine when the useful energy of defrost is concluded. These recommendations can be use immediately by CEE with their industrial refrigeration customers.

Future Work

As alluded to previously, a key part of the work left to be done on this project is an exploration of the effects of the HGD process on the work being done by the compressor. This arises from two considerations that cannot be ignored in a complete analysis of the process. First, any gas that comes back to the suction side of the system is essentially being circulated through the compressor without accomplishing any useful task. The other key consideration is the additional heat load on the system that results from essentially operating a condenser in the refrigerated space.

More data collection will be necessary to establish statistical data on how the process is affected by different operating conditions. This could include different frost levels, system operating pressures, ambient conditions, system loading (seasonal variation), etc.

The flow meters that were selected for use in the design can be easily recalibrated to measure higher flow rates of hot gas. This will allow the system to collect complete and accurate data for the entire duration of the defrost.

An in depth exploration of sublimation during defrost should also be carried out to see how various defrost parameters affect the relative quantities of sublimated frost as well as evaporation of melt water. From the data collection that has already been done, it is apparent that lower defrost temperatures reduce the effects of sublimation and evaporation.

Another useful piece of data could be obtained by doing long term monitoring of the ambient outdoor conditions as well as the temperature and relative humidity within the refrigerated space. This information could be analyzed along with monitoring of door activity (and any other sources of infiltration) to see the effects on the rate of frost formation and the characteristics of the frost body formations (density, layer thickness, etc.).

A variable frequency drive could be installed on the evaporator fans to investigate how variation in the fan speed affects the rate at which frost forms and how demand defrost can be used when variations in fan speed are present.

A final piece of verification could be obtained through measurement of the liquid return flow rate; this could provide an even higher level of confidence in the other flow rates that are being collected.

The analysis conducted on the hot gas defrost process by the PSUHGDSDT has focused on the transfer of heat and mass at the evaporator coil. It is important to note that this is only a preliminary analysis that does not take into account the effects of this process on the overall efficiency of the refrigeration system. Nonetheless, a key step in achieving this goal has been taken in that our system provides a means of quantifying how much and in what places the heat and mass transfer have taken place. Our customer, CEE, will be able to make use of this information in carrying out an analysis that takes into consideration the effects of this heat and mass transfer on compressor work as well as its effect on the heat load experienced by the system. When such an analysis is completed, our customer will be able to generate a kWh potential savings number that will satisfy the electrical utility's requirements to include HGD improvements as an Energy Efficiency Measure (EEM) in a typical refrigeration energy study.

Conclusion

During the 24 four weeks the PSUHGDSDT has met all of the PDS, followed the mission statement and succeeded in making useful findings during our testing and analysis phase. The minimally invasive recommendations can operate in the cold environment, it is less expensive than our target, it will yield the necessary data accurately, it is very safe and it was completed in the time frame allotted by the university. In accordance with the project requirements, a flow separator, heated enclosure, and melt water measurement system have been designed, fabricated, installed, instrumented, calibrated, and used in regular operation to collect data for defrost efficiency calculations. Also, through the analysis process the team made some interesting findings: the melt water temperature relationship to events in the defrost and that the mass flow rate of the hot gas far exceeds industry expectations. The PSUHGDSDT was successful in designing and completing a ground breaking and very useful project during the 2002-2003 school year.

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