



The Cold Front

The Electronic Newsletter of The Industrial Refrigeration Consortium

Vol. 8 No. 3, 2008

BACK TO BASICS - *FROST*

In this article, we focus on the operation of air-cooling evaporators in industrial refrigeration applications at temperature below freezing. These heat exchangers are generally applied to control the environmental conditions in holding freezers, dynamic blast freezers, stationary blast cells, refrigerated docks, and other lower temperature conditioned spaces found in food manufacturing and distribution facilities. We review the factors that influence the formation of frost on the evaporator surfaces and discuss how frost accumulation impacts coil performance.

INTRODUCTION

Air cooling evaporators are refrigerant-to-air heat exchangers widely used in industrial refrigeration, commercial refrigeration, and heat pump systems. Known as “plate-finned” heat exchangers, these units consist of multiple rows made up by a series of parallel circuits (i.e. individual tubes).

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Refrigerant evaporates inside the tubes as it absorbs heat from air flowing over the outside surface of the tubes. Most air cooling evaporators are equipped with external fins to increase the surface area available for transferring heat.

When air cooling evaporators operate both with coil surface temperatures both below 32°F (0°C), and entering air dew point temperatures above the coil surface temperature, moisture from the air being cooled will precipitate onto the fins and tubes of the coil forming frost. The formation and growth of frost on the evaporator causes a decrease its cooling capability.

What is the root cause of capacity decrease from frosted coil?

- a. *Increased air-side pressure drop; thereby, decreasing air flow through the coil*
- b. *Increased resistance to heat transfer between the air and the refrigerant due to the insulating effects of the frost*
- c. *All of the above*
- d. *None of the above*

If you answered “c.”, you are correct. There have been a number of published papers in the past highlighting this phenomena including: Stoecker 1957, Cleland 2005, Mago and Sherif 2005, and others. Aljuwahel, et al. 2008 confirmed that the single greatest factor reducing evaporator capacity due to frost accumulation is the decrease in air flow rate due to its effect on air-side pressure drop as originally suggested by Stoecker (1957).

UPCOMING AMMONIA COURSES

Principles & Practices of Mechanical Integrity for Industrial Refrigeration Systems

November 5-7, 2008 Madison, WI

Intermediate Ammonia Refrigeration

December 3-5, 2008 Madison, WI

Engineering Safety Relief Systems

December 15-19, 2008 (9-11 am CDT)

Anywhere via the web

Process Safety Management Audits

January 14-16, 2009 Madison, WI

Ammonia Refrigeration: Uncovering Opportunities for Energy Efficiency Improvements

February 11-13, 2009 Madison, WI

Introduction to Ammonia Refrigeration

March 4-6, 2009 Madison, WI

Ammonia Refrigeration System Safety

April 7-9, 2009 Madison, WI

Design of NH₃ Refrigeration Systems for Peak Performance and Efficiency

September 21-25, 2009 Madison, WI

Introduction to Ammonia Refrigeration

October 7-9, 2009 Madison, WI

See www.irc.wisc.edu/education/ for more information.

NOTEWORTHY

- Mark your calendars now for the **2009 IRC ADVISORY MEETING** (May 5) **AND R&T FORUM** (May 6-7) in Madison.
- Send items of note for next newsletter to **TODD JEKEL**, tbjekel@wisc.edu.

FACTORS INFLUENCING COIL CAPACITY DURING FROSTING CONDITIONS

What are the factors that control how fast my evaporator’s capacity will decrease due to frosting?

There are a number of factors that influence the rate of frost accumulation on a coil resulting in increased air-side pressure drop and reduced air flow rate through the coil.

- Fin spacing:** Sometimes referred to as “fin pitch”, the density of fins applied to an evaporator will have a dramatic effect on the susceptibility of coil frosting and the resulting capacity loss due to blocking air flow. Although increased fin density (decreased fin spacing) may be desirable because it offers the potential to enhance the surface area available for heat transfer, the reduced spacing between fins allows frost to grow and decrease the open area available for air to flow; thereby, causing the coil to “plug” more rapidly under frosting conditions. Therefore, a balance between a fin spacing that provides adequate coil surface area but does not cause a rapid buildup of frost which restricts air flow is required.

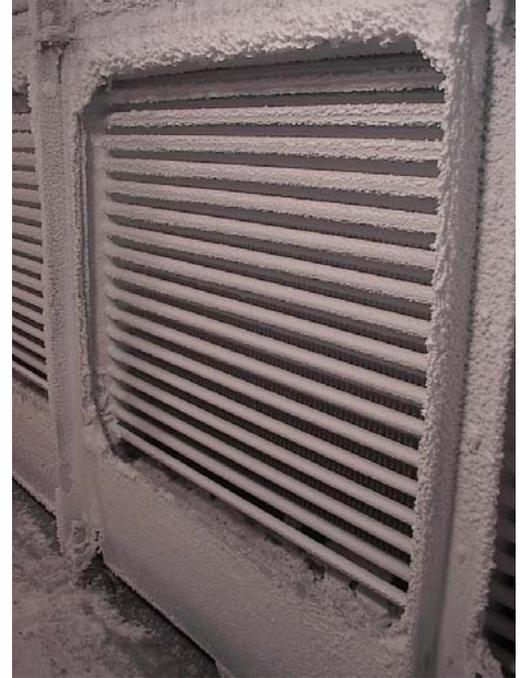


Figure 1: An evaporator coil with the first two tube rows fin free.

In low temperature freezing systems, there are some coil designs that have variable fin spacing, that is, one or more rows of tubes that are without fins to avoid frost plugging. Figure 1 shows an evaporator for a low temperature blast freezer where the first two rows of the coil are tubes without any fins. Because moisture is being extracted from the air stream as it moves from the entering to the leaving side of the evaporator, successive rows in this coil have increased fin density to provide surface area while mitigating the plugging effects of the frost accumulation. The table below provides some basic guidance for typical fin spacing on coils over a range of operating conditions.

Table 1: Review of typical evaporator fin spacing over a range of space operating conditions.

Operating Temperature Range	Moisture/Frost Load	Typical Fin Pitch [fins per inch (cm)]	Comments
-25°F (-32°C) and colder	Heavy-Moderate	0-3	Consider variable fin pitch coil
25°F (-32°C) to +10°F (-12°C)	Heavy	0-3	Consider variable fin pitch coil
	Moderate-Light	2-3	
+10°F (-12°C) to +35°F (2°C)	Heavy-Moderate	3	
	Light	4	
+35°F (2°C) to +50°F (10°C)	Heavy-Light	4-6	Avoid high fin density coils in areas with airborne particulates (e.g. packaging areas).

It is important to work with your evaporator manufacturer to select an appropriate coil once you understand the operating environment for that coil.

- Coil Location:** Coils located in regions with supersaturated moisture will experience a much higher rate of frost accumulation and plugging. Figure 2 shows an example of warm, moist air from a dock infiltrating into a freezer. Because the infiltrating air is more buoyant, it rises to the ceiling. The rapid cooling of the supersaturated moist infiltrating air causes crystals of ice to form in the air rather than on the coil surface. If an evaporator is located immediately above the door opening, it will see a significant load of supersaturated moisture and will quickly plug the face of the coil with frost. The accelerated rate of frost accumulation on the entering side of the coil surface is due to impaction and interception of the ice crystals onto the coil surface. If the moist dock air had an opportunity to blend with the colder drier freezer air, the rate of frost-induced plugging on the coil would be reduced.

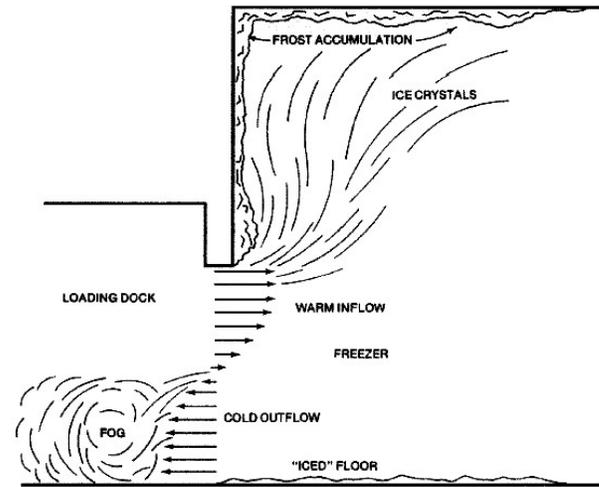


Figure 2: Air flow patterns from a dock to a freezer [ASHRAE *Refrigeration Handbook*, 2002].

- Moisture Load:** In applications with significant moisture loading, the rate of frost accumulation can rise dramatically - accelerating the capacity loss. One way to characterize the severity of the moisture load in terms of the “sensible heat ratio” (SHR). The sensible heat ratio represents the ratio of the space sensible load to the space total load as given by:

$$SHR = \frac{Q_{sensible}}{Q_{total}} = \frac{Q_{sensible}}{Q_{sensible} + Q_{latent}}$$

The term $Q_{sensible}$ represents that portion of a heat load that causes the air temperature to rise while Q_{latent} is the portion of the heat load causing a moisture increase. As the moisture or latent load in a temperature-controlled space increases, the sensible heat ratio decreases and operating evaporators will experience increased difficulty in removing the moisture needed to maintain space humidity levels. This is especially relevant for those evaporators operating in low temperature environments (below 32°F/0°C).

A number of past investigators have characterized envelopes of operating conditions that lead to moisture and frost problems in conditioned spaces. Figure 3 shows a series of three (3) process lines on a section of a low temperature psychrometric chart. The situation is typical of what happens when air from a less conditioned dock space infiltrates to a lower temperature storage freezer in an air flow pattern similar to that shown in Figure 2.

In the three cases that are shown, the infiltrating air from the dock is at a constant dry bulb temperature of 50°F (10°C) while the relative humidity varies from 60% (case 1) to 20% (case 3). The lowest surface temperature in the freezer space is the evaporator coil which operates at -10°F (-23°C) – a point commonly referred to as the “apparatus dew point temperature” or ADP.

When the air from the dock enters into the freezer, a mixing process occurs. As the warmer dock air blends with the colder air within the freezer, the mixed air condition progressively moves down the tie line that connects the dock condition to the ADP. Case 1 is labeled as “unfavorable process line” due to portions of the process line being above the saturation curve which leads to a *supersaturated* moisture condition where ice crystals will actually form in the air. Smith (1989, 1992) identified the “unfavorable” frost condition and noted how the presence of this condition adversely impacted evaporator performance as well as causing significant icing effects on other cold surfaces within the freezer.

If the relative humidity of the infiltrating air can be reduced, the infiltration latent load on the freezer evaporator coil(s) is reduced (SHR increase) and the tendency for adverse coil frosting is diminished. Referring to

Figure 3, the process line originating from a dock dry bulb temperature of 50°F (10°C) with a corresponding relative humidity of 30% runs tangent to but does not cross the saturation curve as it approaches the ADP; thereby, avoiding *unfavorable* evaporator frosting. An increasingly favorable frost condition is achieved with further reductions in infiltrating air relative humidity.

How can I minimize or avoid conditions that lead to unfavorable frosting?

To the extent possible, the source of the moisture should be identified and minimized. In cases where moisture originates from infiltrating air, means to reduce that infiltration rate should be pursued. This may require repairing seals, maintaining door control, reducing openings (e.g. for conveyors), and assuring an appropriate pressure balance between spaces at differing conditions. Further

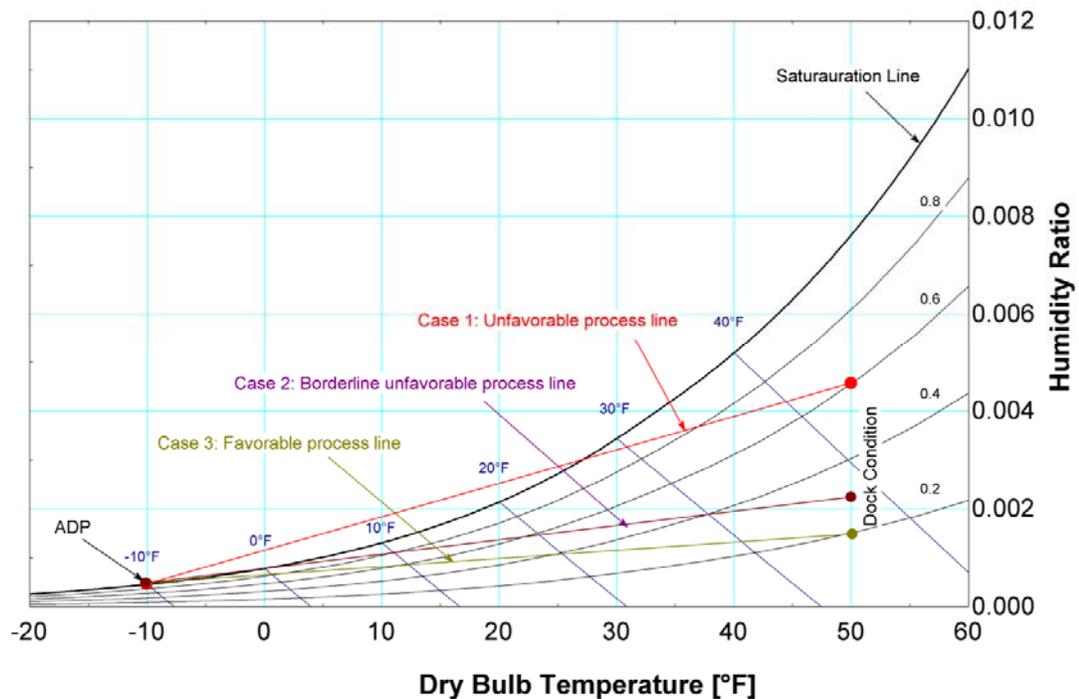


Figure 3: Psychrometric chart showing process lines that range from unfavorable to favorable conditions for frosting (adapted from Cleland 2005).

information on these strategies can be found in past issues of the Cold Front including: Volume 5, Number 3 (2005) and Volume 5, Number 4 (2005) as well as Cleland (2005).

If the source of moisture is from products that are being processed, consider alternative means that can reduce its moisture loss. Strategies for reducing product moisture loss can include: packaging prior to cooling/freezing, pre-cooling product, crust-freeze product using a cryogenic fluid prior to finish-freezing with a mechanical freezing system (flash freezing will create a crust on the product surface to minimize desiccation). Techniques to reduce moisture loss have the added benefit of increasing product yield! Yield savings will almost certainly far outweigh energy cost benefits from reduced moisture loads on evaporators. It is important to realize that, for many low temperature freezing systems, the extent of *unfavorable* frost conditions can be minimized but not eliminated.

For spaces such as holding freezers, one common approach for avoiding *unfavorable* frost conditions is to lower the set point temperature of the dock in order to increase the level of moisture removal at a higher evaporator temperature (when compared to the freezer). Reducing the dock set point temperature to something in the range of 35°F (2°C) will permit air defrosting while providing significantly more moisture removal when compared to a 50°F (10°C) space set point. In some cases, hot-gas reheat is added at the dock evaporator to further increase the space sensible heat ratio.

Figure 4 shows a dock maintained at a 35°F (2°C) dry bulb temperature with a relative humidity of 55%. A process line to the ADP shows it to be slightly *unfavorable* since the saturation curve is narrowly crossed. By adding a small amount of reheat at the dock door to increase the dry bulb temperature of infiltrating air to 50°F (10°C) we are able to drive the state of infiltrating air from *unfavorable* to *favorable*.

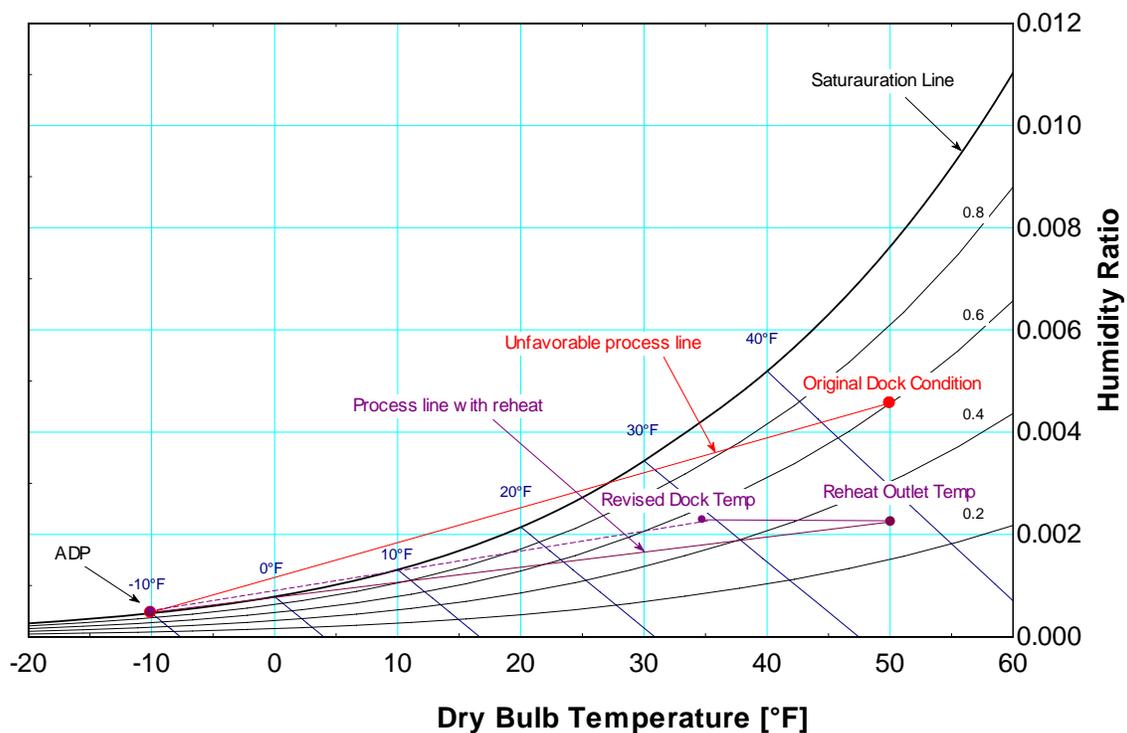


Figure 4: Psychrometric chart showing process lines to improve frosting.

Cleland (2005) offers other strategies for avoiding unfavorable frosting conditions but rightly places a particular emphasis on preventing the infiltration using door protection devices.

- Frost Type: Somewhat related to the previous bullet point, the type of frost will have an influence on the rate of coil capacity decrease due to air flow blockage. Unfavorable frosting conditions leads to the formation of ice crystals directly in the air stream. There is a tendency for these ice crystals to precipitate onto cold surfaces within the space; however, they will ride along on air currents created by operating evaporator fans. The frost crystals will readily adhere to the coil surface by physical impaction or interception; thereby, blocking air flow. Figure 5 shows the structure of unfavorable frost adhering to the surfaces of a variably finned, low temperature evaporator freezing unpacked product and operating with a moderately high TD (difference in temperature between the entering air and the evaporating refrigerant). In this case, the structure of the frost is extremely light and fluffy with minimal bonding to the coil surface. We postulate that, in this case, the coil plugged where the fins began and that the very light, “fluffy” frost grew after the coil blockage. As mentioned previously, this type of frost degrades coil performance more rapidly than a higher density frost as shown in Figure 6.



Figure 5: Low density frost forming on an evaporator due to high coil TD and presence of supersaturated air.

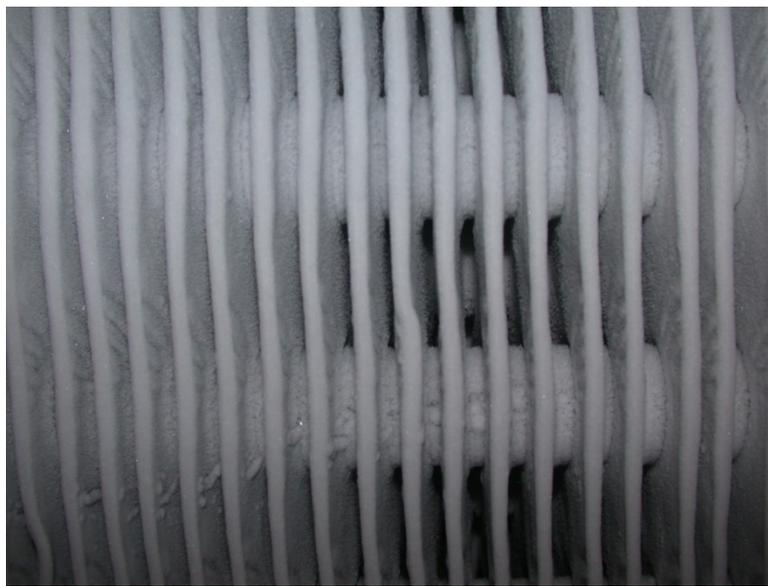


Figure 6: Higher density frost forming on an evaporator.

The higher density frost forming on the coil shown in Figure 6 occurs in spaces with *favorable* frosting conditions. Due to the lack of supersaturated air as well as an operating coil TD of 10°F (6°C), moisture from the air forms on the coil by a diffusion process creating a much more dense frost structure. The higher frost density allows the coil to accumulate significantly more mass of moisture (frost) before adversely impacting coil capacity due to air flow blockage.

MEASURING COIL CAPACITY DECREASE DUE TO FROSTING

How significant is the rate of capacity loss due to frosting?

As mentioned previously, the loss of coil capacity under frosting operation is due to reduced air flow as well as increased resistance to heat transfer. The more significant of these two factors is the capacity loss due to blockage of air flow (Stoecker 1957, Barrow 1985, Seker, et al. 2004, and Yao, et al. 2004, and Aljuwahel et al. 2008). The effects of frost presenting an increased resistance to heat transfer are significantly less important (Stoecker 1957 and Machielsen, C. H. and Kerschbaumer 1989).

Aljuwahel (2006) monitored the performance of a single 37 ton (130 kW) evaporator located in a penthouse in a low temperature storage freezer. Additional details on the coil are given in Table 2.

Table 2: Geometry and operating conditions of the experimentally monitored air-cooling evaporator.

Parameter	Value
Fin pitch	3 fins/inch(0.85 cm)
Face area	88.6 ft ² (8.23 m ²)
Tube diameter	3/4 inch (19.05 mm)
Tube length	18 ft (5.5 m)
Number of fans	5
Fan power @ -30°F (-34°C) air temperature	3.125 HP (2.33 kW)
Rated CFM	60,000 CFM (1,699 m ³ /min)
Number of tube rows	10
Saturated evaporator temperature	-30°F (-34.4°C)
Coil temperature difference	10°F (5.6°C)
Rated coil capacity	37 tons (130 kW)
Fin and tube material	Aluminum
Evaporator coil type	CPR-fed liquid overfeed

The in situ performance of the unit was determined using an extensive configuration of air-side instrumentation arranged to measure entering and leaving conditions (air temperature and moisture

content) as well as the average velocity of air flowing through the actual coil. In addition, data was collected to determine the volume flow rate of air being conveyed by the unit's five (5) fans.

Figure 7 shows the average face velocity of air across the coil during frosting operation over a 41 hr period. The average velocity of air across the frost-free coil is approximately 560 ft/min (2.85 m/s) but that average velocity decreases by nearly 50% to 315 ft/min (1.6 m/s) at the end of its operating cycle. Figure 8 shows the average dry bulb temperature of air entering and leaving the evaporator during frosting operation. The average entering air temperature (i.e. space temperature) is relatively constant at -17.5°F (-28°C) while the leaving temperature decreased from -24°F (-31°C) to -26°F (-33°C) as the coil accumulated frost. The drop in leaving air temperature is a byproduct of the decreased air flow rate through the coil which allows longer dwell time to give up its heat to the refrigerant. Unfortunately, that decreased coil leaving air temperature is not sufficient enough to overcome the drop in air flow rate; consequently, the coil's refrigeration capacity decreases over time as frost accumulates on the coil. The actual measured gross capacity of the coil is shown in Figure 9.

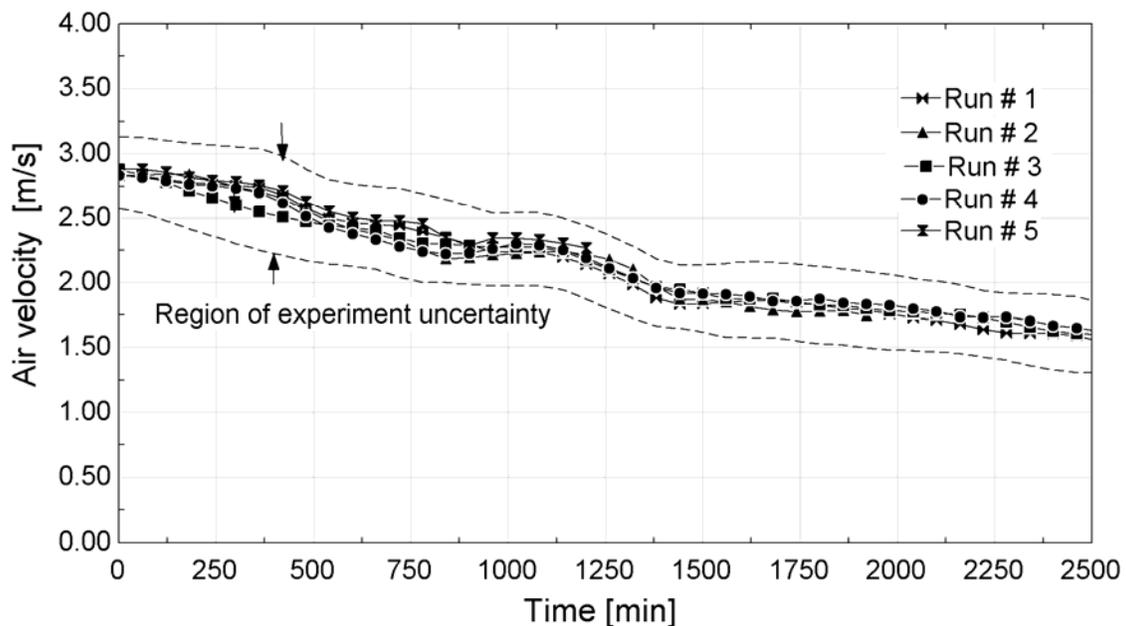


Figure 7: Average face velocity of air across the coil during frosting operation.

The average clean coil capacity over four separate runs is 33 tons (116 kW) and the capacity of the unit decreases to 27 tons (95 kW) after 41 hrs of operation representing a capacity loss of nearly 20%. Two other observations are in order regarding the measured coil capacity. First, the field-measured capacity is 8% less than the unit's rated capacity. Second, the measured evaporator capacity is gross because it does not include fan heat gains. The net effect is that an evaporator's capacity, while operating under frosting conditions, will decrease and the system's operating efficiency suffers as a result. To counter these effects, the accumulated frost must be removed from the evaporator surface on either a continuous or intermittent basis. In the next issue of the Cold Front, we will look at details of the defrost process.

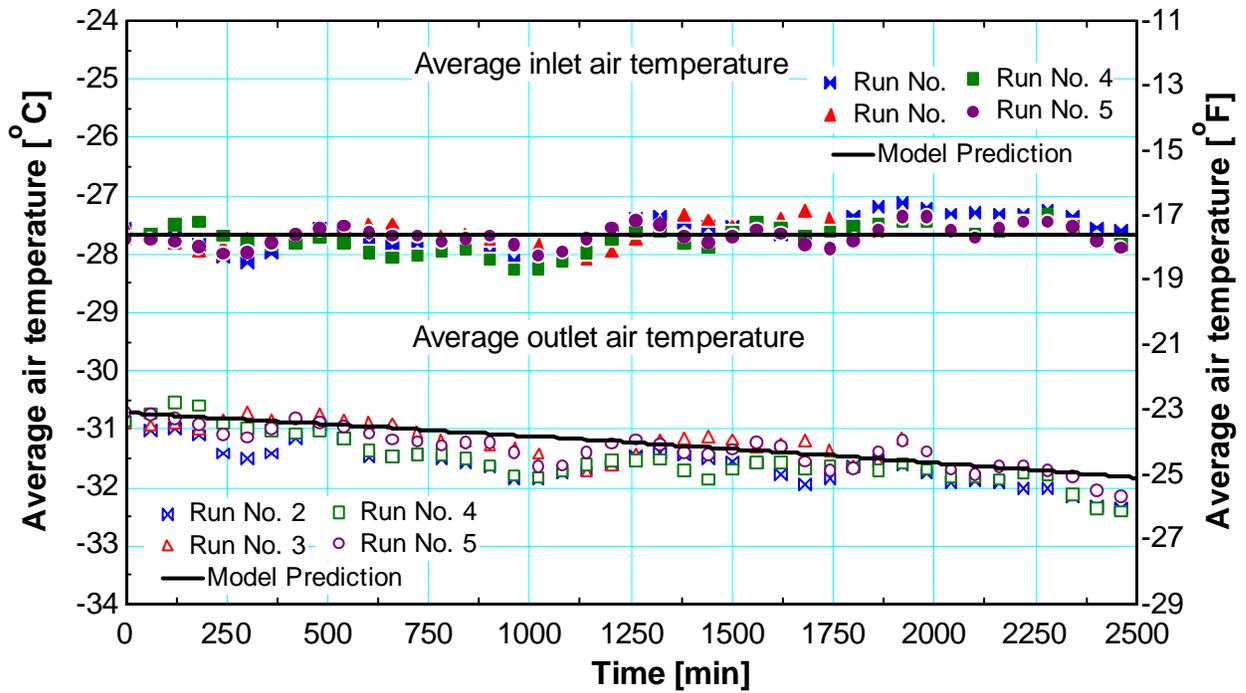


Figure 8: Average coil inlet and outlet temperatures during frosting operation.

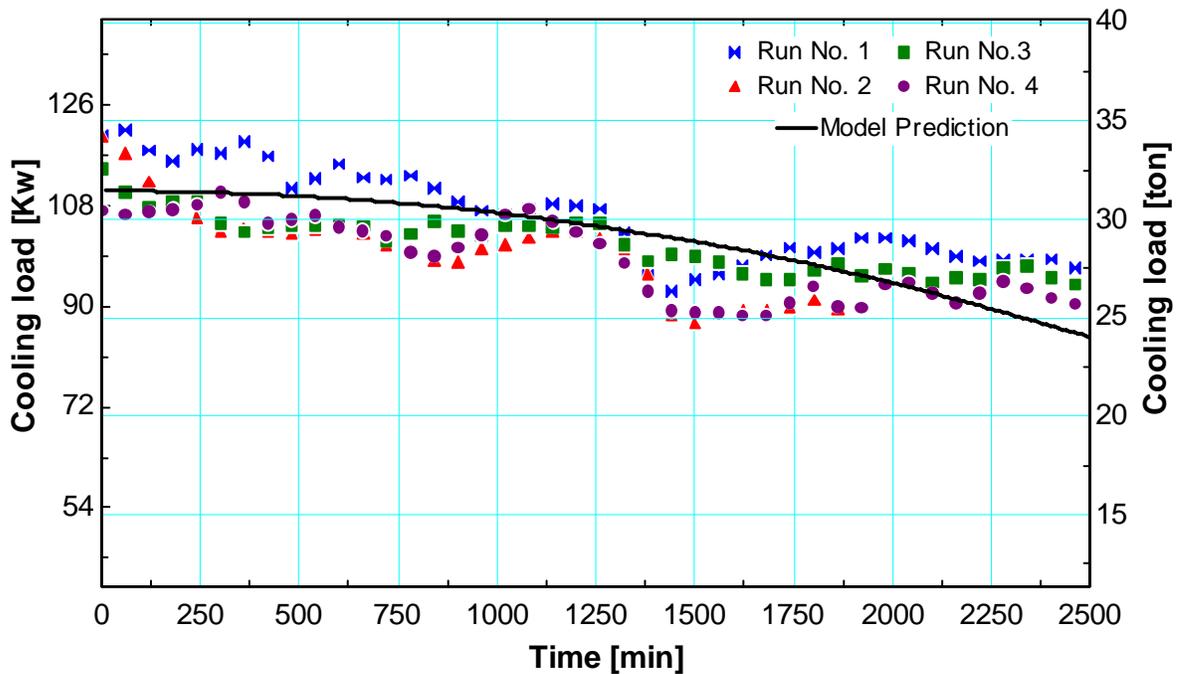


Figure 9: Coil capacity (load) as the unit operates from clean to frosted condition.

ALTERNATIVE APPROACHES

You might wonder: *Are there other approaches that can further reduce or eliminate the need for defrosting evaporators?*

The short answer to this question is “not really.” Some alternative approaches use a liquid desiccant

media such as glycol which is sprayed directly onto the evaporator surface to preferentially absorb the moisture into the freezing point depressed working fluid. As moisture from the air goes into the liquid solution, the concentration of glycol will be reduced and reconcentration becomes necessary to avoid freeze-ups. In this case, the equivalent to a hot gas defrost for a typical evaporator occurs remotely from the unit as heat is added to drive off the accumulated water; thereby, re-concentrating the glycol for reuse.

Another alternative that has been promoted to reduce latent loads is the use of solid desiccants. The solid desiccant system approach can reduce latent loads in temperature controlled spaces but the added cost of the desiccant system operation needs to be carefully evaluated to understand whether or not the total cost of operation will be lowered.

CONCLUSIONS

With the exception of sprayed desiccant units, evaporators operating at lower temperature conditions will result in frost formation on the coil surface. A number of factors influence both the rate and nature of frost formation including: evaporator unit fin spacing, coil location, latent (moisture) load, and frost type or structure. The accumulation of frost on a coil causes its capacity to decrease due to blockage of air flow as well as the insulating effects of the frost layer itself. As a result, a period removal of the accumulated frost layer is required to maintain system capacity and efficiency. Look for a review of defrost in the next issue of the Cold Front. *Questions* – contact Doug Reindl at the IRC – 866-635-4721 or dreindl@wisc.edu.

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PRINCIPLES AND PRACTICES OF MECHANICAL INTEGRITY FOR INDUSTRIAL REFRIGERATION SYSTEMS

NOVEMBER 5-7, 2008

MADISON, WI

New Course

The Industrial Refrigeration Consortium (IRC), through its association with the Engineering Professional Development department at the University of Wisconsin-Madison, is presenting a practical new course on mechanical integrity for industrial refrigeration systems with a focus on ammonia based systems.

What You Will Learn

This course is your opportunity to develop and refine your knowledge, skills, and capabilities in mechanical integrity principles and practices for industrial refrigeration systems. By participating in this course, you will:

- Review the minimum requirements for a mechanical integrity program
- Develop an understanding of those mechanisms responsible for the mechanical integrity failure of piping and vessels
- Obtain information on recommended practices for managing the mechanical integrity of piping, vessels, and other equipment
- Be able to enhance the safety and cost-effectiveness of your industrial refrigeration systems by reducing risks related to mechanical integrity failures

The information presented in this course is structured to allow you to immediately apply what you have learned during this course. Attend this course and your plant will benefit!

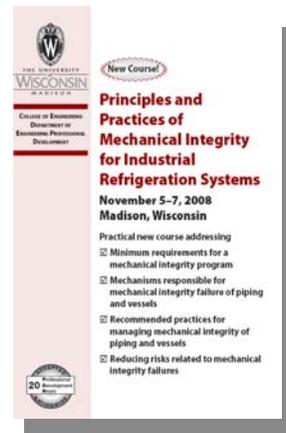
Who Should Attend

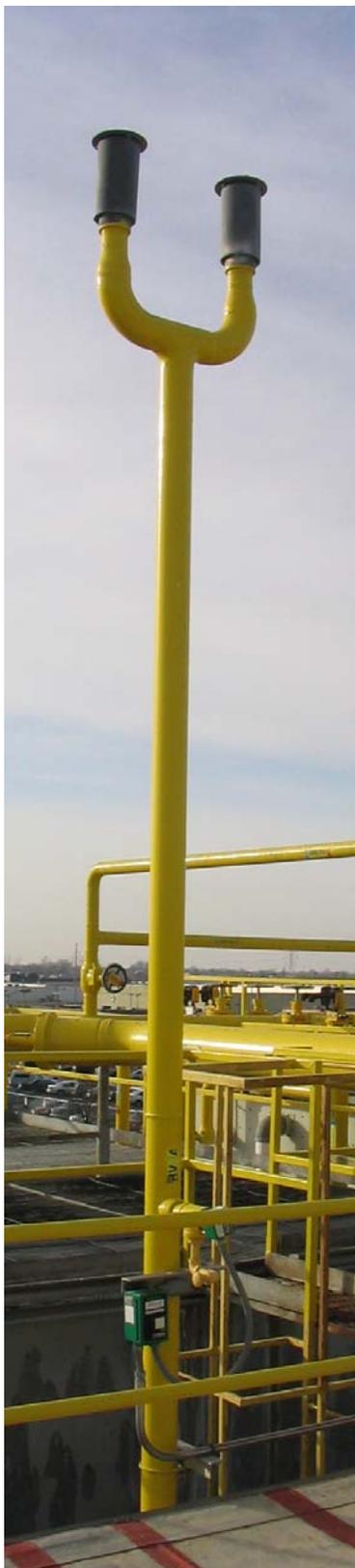
This course has been designed for

- Plant engineering staff
- Utility supervisors
- Refrigeration system operators
- PSM coordinators
- Contractors doing mechanical integrity work
- Others interested in understanding the basic principles and practices of mechanical integrity for industrial refrigeration systems

Questions?

Contact Doug Reindl, (608) 262-6381, dreindl@wisc.edu. Further information on this and other upcoming ammonia courses can be found at <http://edu.engr.wisc.edu/catalogs/refrigeration.lasso>.





RELIEF SYSTEM DESIGN WEBCOURSE!

This third annual event will be held via the web **December 15-19, 2008** at **9-11 am Central**. This workshop is an ideal opportunity to develop or improve your understanding of engineered safety relief systems. Our primary focus is industrial refrigeration systems but many of the principles we will discuss apply equally to other applications as well.

Whether you are an end-user, equipment manufacturer, design engineer, or contractor, this course will help you build your capabilities in the area of the principles and practices of engineering safety relief systems. Participate and develop your understanding of:

- ✓ Codes and Standards related to safety relief systems
- ✓ Key aspects of engineering code-compliant relief systems
- ✓ Capacity determination for non-standard equipment like heat exchangers
- ✓ Methods for proper sizing of relief vent piping, including headered vent systems

In addition to the course, the IRC has developed a web-based safety relief systems analysis tool. This powerful tool has a high degree of flexibility to analyze, engineer, and document safety relief systems for industrial refrigeration applications. The tool features:

- ✓ Graphical user interface to configure relief system to be analyzed
- ✓ Ability to handle headered systems & multiple relief scenarios
- ✓ Quick and accurate algorithm to solve compressible flow equations
- ✓ Relief valve selection wizard
- ✓ Equivalent lengths for elbows & fittings included
- ✓ Detailed compliance checks for each system component
- ✓ One-click reports for easy printing

Access to the tool is provided free of charge to those completing this course. A brochure for the course is available on our website www.irc.wisc.edu, or by clicking <http://www.irc.wisc.edu/?file&id=248>.