Technical Note

Performance Optimization Techniques for Rooftop HVAC Equipment

Rooftop HVAC equipment plays a critical role in maintaining proper indoor air quality in most commercial buildings. The installation and condition of this equipment directly affects operating costs, equipment life expectancy, occupant comfort and building tenability. As such, optimizing equipment performance is a high priority for all building stakeholders.

This paper discusses the use and benefits of infrared (IR) thermography to assess HVAC system functional performance. Practical examples will identify acceptable shortcuts versus unacceptable practices when using thermal imaging, and highlight best practices to reduce chances of missing a real issue or finding a fake issue. We will see how thermal imaging, when performed correctly, can expedite commissioning, maintenance and forensics studies, and ultimately result in significant cost savings to clients.

UNDERSTANDING HVAC AND BUILDING SCIENCE

It is paramount that a thermographer has a thorough understanding of the equipment being surveyed in any application. In this case, an understanding of basic HVAC equipment operation is necessary to properly assess IR images of the equipment and analyze overall system performance. This paper will briefly review a commercial packaged rooftop air-conditioning unit (RTU), which includes the evaporator and condenser coils/fans and other accessories within a single housing. We will also discuss condenser water piping, including the open loop from the cooling tower and the closed loop to the building A/C units.

Relevant operating parameters for these systems will be mentioned within the individual case studies presented. These examples show the power of IR in analyzing HVAC system operation. Readers with a comprehensive HVAC background will be able to apply these concepts to myriad other system types.

In addition to understanding how HVAC equipment functions, and expected temperatures of the various components, it is equally important to be aware of building science and environmental factors that can influence the images captured by your IR camera. Thus, an HVAC technician needs to understand IR.

IR SURVEY CHALLENGES

Reflections and background temperatures pose one of the most significant challenges during outdoor IR surveys. Sources can typically range from -50°F for a clear sky to 150°F for nearby motors to everything in between and beyond. Bear in mind that the roof deck and adjacent buildings offer reflections as well - sometimes as a result of being genuinely hot and other times because of reflections from another source.

Reflections can usually be identified or minimized by using creative photo angles to change reflection sources. Placing an IR shield (cardboard) between the surface and source - or when safe, applying electrical tape to low-emissivity (highly reflective) surfaces - can also help obtain more accurate readings. Most elements that will be surveyed during a rooftop HVAC inspection have a minimum emissivity of 0.85. So, other than unpainted metal surfaces (pipe insulation jackets, flashing, etc.), temperature readings will often be accurate enough to reveal most problem areas. Settings for reflected and ambient temperatures and emissivity can be fine-tuned in situations where more highly accurate temperature readings are desired.

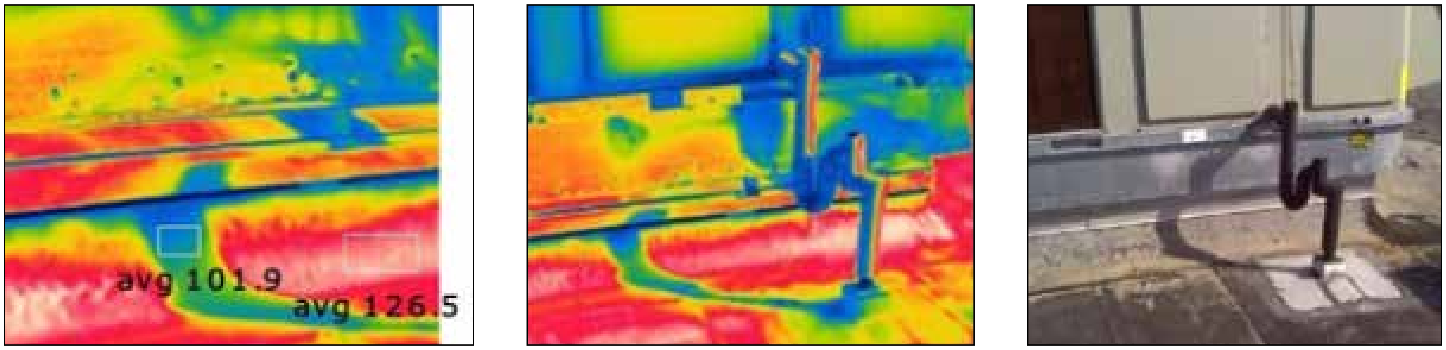

Figure 1: Three images of an RTU curb connection: Left - close-up IR; Center - zoomed out IR; Right - visible.

Long-term shadows from buildings or equipment cause a genuinely cooler area versus the sun-exposed surface of a component. This often occurs on the side of a housing and the nearby roof. You will need to independently interpret the results of the sunny and shaded areas or resurvey at a different time of day.

Background temperature influence can also be mitigated by changing the photo angle, getting closer to the equipment, and, if necessary, by ignoring temperatures at the immediate edge of the equipment. Your camera's resolution directly impacts the distance you need to be from the equipment for accurate readings. IR thermometers (single temperature spot temp guns) are not recommended for most HVAC surveys, as using one would be equivalent to performing a visible survey while looking through a pinhole. All IR images in this paper were captured at a resolution of 320 x 240 on a FLIR T300.

To demonstrate how all of these elements can impact the interpretation of thermal images, consider the IR and visible images of a typical RTU in Figure 1. In the photo on the left, an abnormal temperature distribution is discovered in the form of a cold streak down the vertical face of the curb. When you stand farther back, the center image shows this is actually just a shadow cast by the condensate riser. The visible image on the right confirms the source is truly a shadow, and thus, there is no problem. Taking the average temperature in an area, in the left image we see that the shadow is cooler than the rest of the roof deck by about 25°F. Another tip is that as you rotate around, the cold streak does not move, but rather stays in the same location, confirming that the roof deck in that area is genuinely cooler and the streak is not a reflection. Also, this condensate piping is wrapped with black elastomeric insulation, thus no significant reflections would be expected.

Next, looking at the curb, you see that the IR patterns are abrupt and chaotic, which is characteristic of this shiny, unpainted metal. On the painted RTU itself, the temperatures are more reliable. You could either ignore the curb readings or apply electrical tape if you desire a realistic temperature.

Finally, if you focus on the non-shadowed roof deck, you will note that it is a mostly uniform temperature that mildly cools as it rises up the curb and reaches vertical, thus changing angle relative to the sun. You can also note differences in the exposed roofing materials (dirty vs clean areas, tar, patches of different materials, etc.). These are more easily identified if visible images are captured simultaneously.

USE YOUR TRAINING TO SURVEY SMARTER

The larger point here is to look at the big picture – both in terms of the IR image and your visible surroundings. You can combine knowledge of HVAC systems to know the likely areas where to look and knowledge of building science to know how to look correctly when using thermography. But if you get tunnel vision when using your camera, you could find nonexistent problems or miss truly major issues, neither of which is acceptable to your client or our profession. On a related note, always be fully aware of your surroundings when on a roof. There are many severe hazards up there - roof edges with no parapets, belts and fans with no guards, exposed energized electrical components, tripping hazards, etc. Being aware of the big picture during thermal surveys will keep you safe, and make you effective.

Incorporating IR surveys into your existing IOM and inspection procedures for HVAC systems can expedite detecting problems and thereby optimize equipment performance. Some examples include:

- Non-contact inspection of moving parts – e.g., detecting overheating bearings since most pumps do not have vibration sensors calibrated and wired back to a building automation system (BAS)
- Detecting air pockets at high points in piping and coils
- Detecting which coils are operating and whether there are any abnormal areas
- Indirectly detecting air and fluid leaks
- Estimating operating temperature ranges of process air and fluids
- Detecting compromised duct and piping insulation
- Determining time duration for equipment operation to reach steady-state
- Rapidly cross checking duct/coil temperatures against BAS control points during commissioning

When a thermal survey is performed at system startup or as part of the functional performance tests (FPTs) during commissioning, ownership can use this information as baseline data to facilitate on-going predictive maintenance. When performed as a forensics study, the thermal survey can often reveal the root problems and confirm hypothesis with hard evidence. Further, since a picture says a thousand words, supplementing reports with thermal images can more clearly highlight problem areas. With thoughtful presentation, this information can become more easily understood by personnel outside of the HVAC profession – for example, CFOs.

CASE STUDY 1 – POOR INSTALLATION OF A PACKAGED RTU AND CURB

Figure 2 shows visible and thermal images of a supply air duct leak at a packaged rooftop air conditioning unit (RTU). This unit serves a mall retail tenant who had been experiencing cooling problems since the original installation about 6 months prior. The tenant's construction team had determined that the RTU was undersized and was planning to replace it with a larger unit. Our thermal survey quickly revealed that the primary culprit was actually poor duct connections and a break in the gasket between the RTU and the curb. The result was that much of the supply air was leaking out to the roof deck rather than cooling the tenant space.

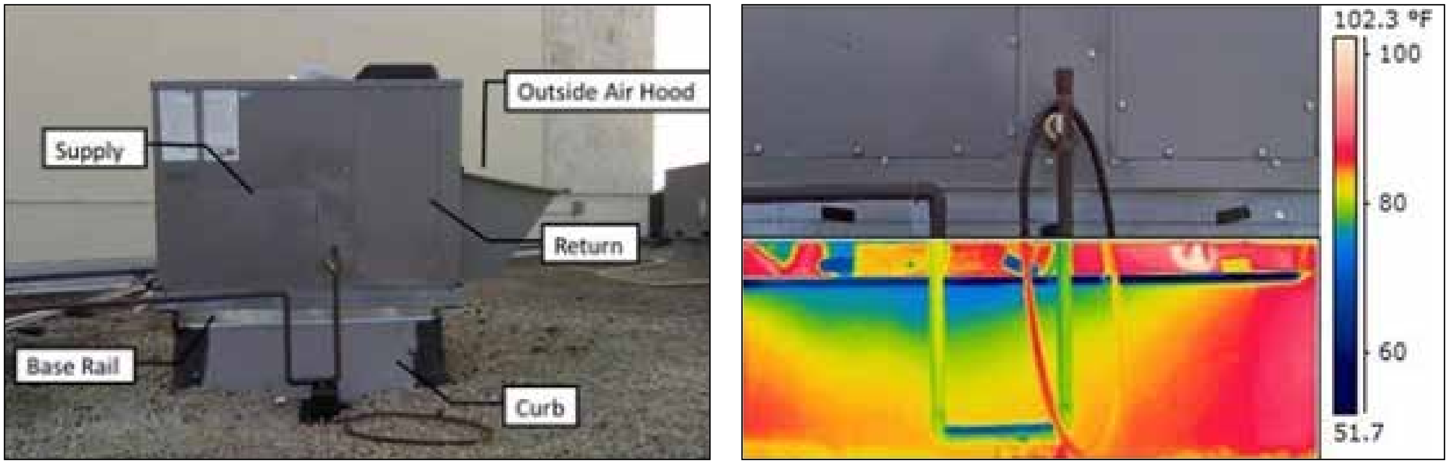

Figure 2: Visible photograph of a packaged RTU serving a retail tenant, with major components labeled (left) and a close-up of the center area, with a superimposed IR image revealing a distinct air leak (right).

The thermal image in Figure 2 shows a clear gradient with the coldest portion at the compromised area of the gasket, and gradually warming in a radial pattern as you get farther from the supply air leak. Note that the IR camera does not see the 55°F supply air leak directly but instead sees the effect of the cold air impinging on the roofing over the curb. Running our hand along this area we were able to confirm the leak.

To highlight the value of relative temperature relationships over highly accurate absolute temperatures, Figure 3 shows the full uncropped IR image used in Figure 2. If we assume that the RTU housing, roofing over the curb, and the tar patch are all ε=0.95 (left) versus ε=0.85 (right), the absolute difference is 1°F- 20°F. The difference is in the higher range for the RTU housing and tar, which is expected since their real emissivity values are slightly lower than the roofing here. But for our intended purposes, these differences are trivial, and the emissivity setting does not affect the displayed IR image if you set the temperature range to auto-adjust. You should obviously estimate the emissivity within reason, however, since ε=0.05 for the above example would have given nonsensical readings of 175°F-310°F.

In general we simply ignore the flashing from our analysis due to its low emissivity, but you can note the three electrical tape strips we placed there to demonstrate its true temperature pattern versus the reflections.

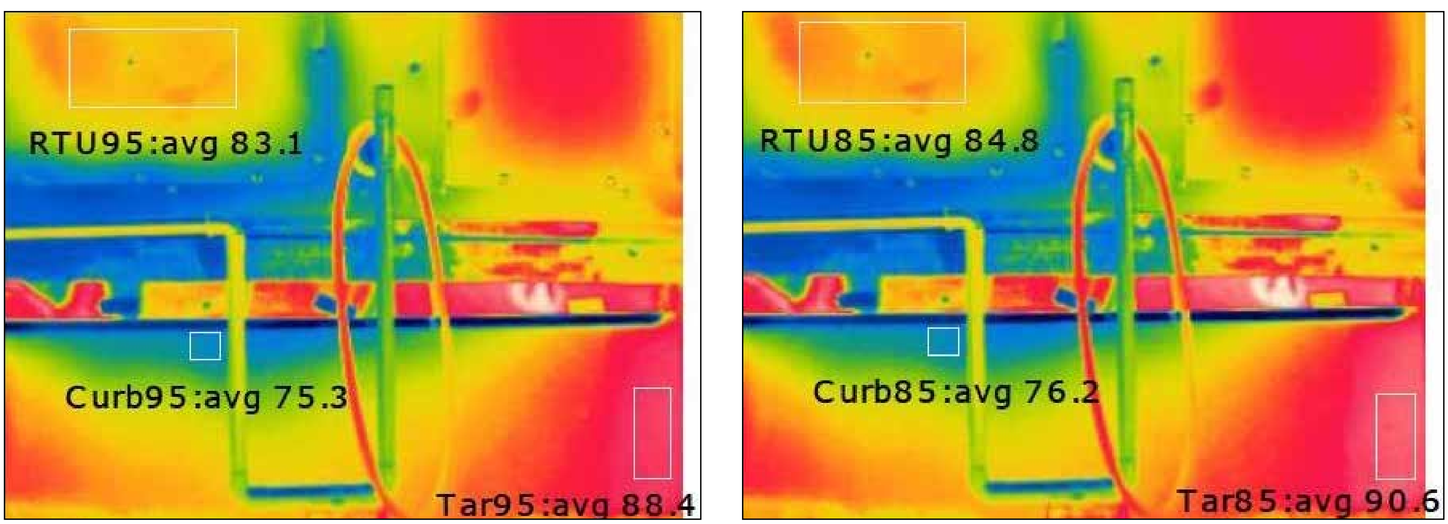

Figure 3: The same IR image from Figure 2, with "default" overall ε=0.95 (left); and adjusted ε=0.85 (right).

Because the supply air duct connection was not properly installed on this unit, the air leak was blowing directly on the inside of the insulated curb as well. The curb's exterior surface temperature dropped to around 70°F as shown in Figure 4, which is well below local outdoor dew point and was saturating the roof deck and occasionally dripping indoors. The excess air was subsequently leaking out where the curb gasket had been compromised as shown previously. No condensation would be expected back on the leak in Figure 2 because the "local" dew point at that area would be the conditioned supply air itself, rather than the humid outdoor air. Also note that the supply air temperature itself was around 55°F. The warmer temperatures displayed in these examples are due to curb conduction and outdoor radiant loads.

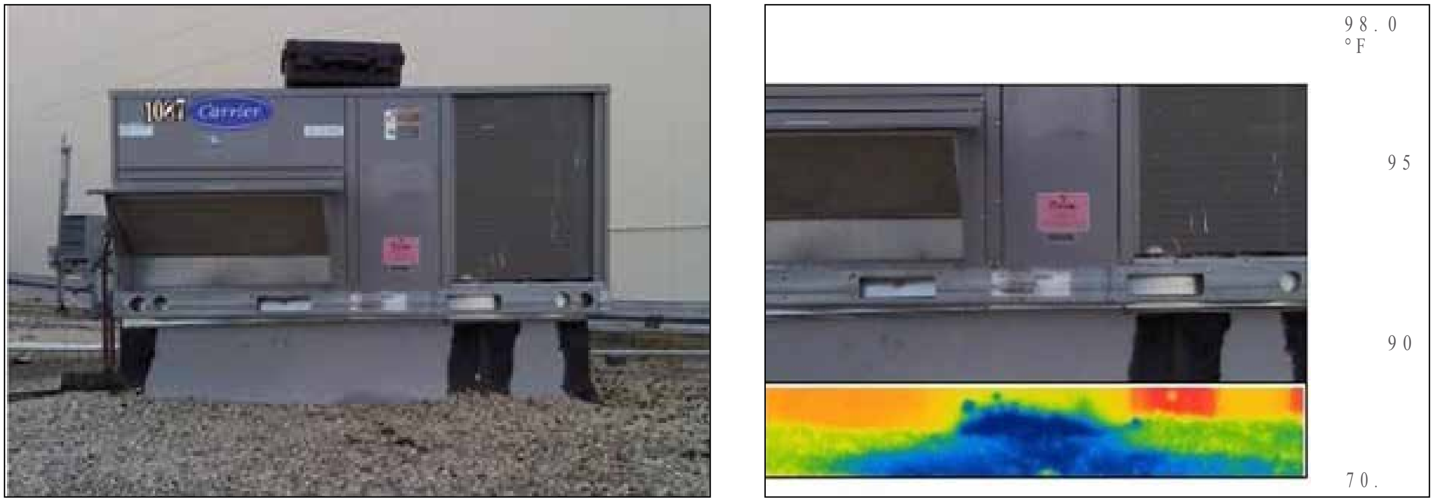

Figure 4: Visible photograph of the same packaged RTU, front view (left) and a close-up of the center area, with a superimposed IR image revealing excessive sweating (right).

Note that if the return duct connection had an equally significant leak, it would not be as directly obvious because it would be drawing outdoor air into the curb, thus not creating a ΔT from this view. For this reason, be aware of the ambient and reflected temperatures relative to the process fluids you are measuring.

We have found that picture-in-picture (superimposed) deliverables with a rainbow color palette are more readily understood by nontechnical clients – blue is cold, red is hot, and the problem area is isolated on top of a visible picture for clarity. When incorporated correctly, the IR image adds a clear empirical component to the reports and streamlines future discussions and actions. Providing the conclusive image in Figure 2 to the tenant resulted in the installing contractors immediately repairing the installation errors at no additional cost. This was a net savings of approximately $7,500 from their originally requested upgrade fee. The tenant's space is now cooling properly with no known reported issues since the repair.

CASE STUDY 2 – DIRTY WATER LOOP

The second case presented is at a high-rise residential condominium building. This system includes a water source heat pump (WSHP) in each condo unit. Closed loop piping pumps water from the WSHPs to a heat exchanger, which drops the temperature by about 10°F. An open piping loop pumps water on the other side of those heat exchangers, which increases the water by about 10°F, and then to a cooling tower to ultimately reject the heat from the building. Actual operating temperatures vary significantly throughout the day and year. But the temperature change (ΔT) across the heat exchanger should be approximately the same on both sides of the heat exchanger under most operating conditions.

The pumps and heat exchangers are typically in a room at the roof deck adjacent to the cooling tower, as shown in Figure 5. Many WSHPs in this building would continually trip off on safety, especially near midday on weekends (peak occupancy and peak solar heat gain). That indicates that the closed loop water into the building was reaching upwards of 100°F, instead of the 87°F typical maximum design.

The space was surveyed near 6 pm in July. The outdoor wet bulb temperature was about 71°F, which means we would expect 78°F water from the cooling tower since the tower was selected for a 7°F approach. To see the overall operating condition of the condenser water system, the mechanical room was scanned with an IR camera. The cooling system was not under a heavy load since it was the evening, and none of the WSHPs were tripping at that moment. But the root problem was still apparent.

Figure 5: Visible photograph of a rooftop mechanical room with pumps, piping, and heat exchangers.

Figure 6 shows the mechanical room with a superimposed thermogram and the adjacent table shows the pipe surface temperatures using the average within an area. The abnormal temperatures (open loop is more than five times the ΔT of the closed loop) indicate restricted flow across the heat exchanger. The pressure drop across the pumps confirmed restricted flow. Excessive debris in both loops from poor maintenance had clogged the small channels in the heat exchanger and rendered it ineffective. An alternate contractor was requested to perform a chemical cleaning and flushing on the two loops. Within five minutes of cleaning the two loops, the system temperatures equalized and have been running trouble-free ever since.

Figure 6: Same as Figure 5, with a superimposed IR photo showing relative condenser water piping temperatures.

Pipe Description	Average Pipe Surface Temperature		
	From	To	Delta T
Cooling Tower	77.0°F	88.1°F	11.1°F
Building	89.5°F	87.4°F	2.1°F

This building has a BAS monitoring temperature and pressure points across each pump. Had it been collected, control system trending data could have easily predicted this situation by watching the pressure and absolute degree Fahrenheit climb, and the ΔT drop over the past several months, before it caused such severe results. However, as is unfortunately common, the controls system was only partially installed and maintained, so the data was not useful. The thermometers in the piping ports were mostly broken as well.

The emissivity of the painted piping is near $\varepsilon=0.85$ and there is no pipe insulation (other than the minor resistance of the steel piping itself). Thus, temperature readings captured with the IR camera are reasonably accurate and equal to the fluid temperature. The IR survey correctly and rapidly identified the root cause, and provided empirical evidence to the ownership and maintenance personnel.

The original contractor had provided calculations incorrectly showing that the closed loop pump capacities should be increased. The owner sought a second opinion. Using thermography reduced our labor in the field and saved the owner approximately $50,000 by not changing the pumps.

SUMMARY

Thermal imaging offers a rapid and empirical means of troubleshooting many aspects of HVAC system operation. Using IR as a diagnostic tool is valuable at all phases of the HVAC equipment lifecycle, from startup to predictive maintenance to forensics investigations. This powerful tool can identify issues that are often missed by even the most sophisticated controls systems.

This paper offers insight to the benefits and challenges of using IR to assess rooftop HVAC equipment. With a thorough understanding of HVAC and IR theory, these concepts can be adapted to myriad other types of HVAC equipment and installations. If you experiment with your IR camera and survey different parts of HVAC equipment (or anything), you will start finding more innovative solutions.

ACKNOWLEDGEMENTS

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