

COMPARATIVE ANALYSIS OF A DESIGN TOOL
TO FIELD STUDY DATA FOR AN UNGLAZED
TRANSPIRED SOLAR COLLECTOR

by

Chelsea Lynn Guenette

A thesis submitted in partial fulfillment
of the requirements for the degree

of

Master of Science

in

Mechanical Engineering

MONTANA STATE UNIVERSITY
Bozeman, Montana

January 2016

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ACKNOWLEDGEMENTS

I need to thank several people for their help and support to complete this work. First I would like to thank my parents. They have always encouraged me to follow my passions and provided all the support I could ask for throughout my higher education. Thank you to Kevin Amende and Dan Stevenson at Montana State University for continually giving me inspiration and opportunities to learn, explore and develop my skills, both as an engineer and researcher. I would also like to thank the members of my committee and the members of the Montana State University Heating, Ventilating and Air-Conditioning Lab for providing the support and feedback required to accomplish this work.



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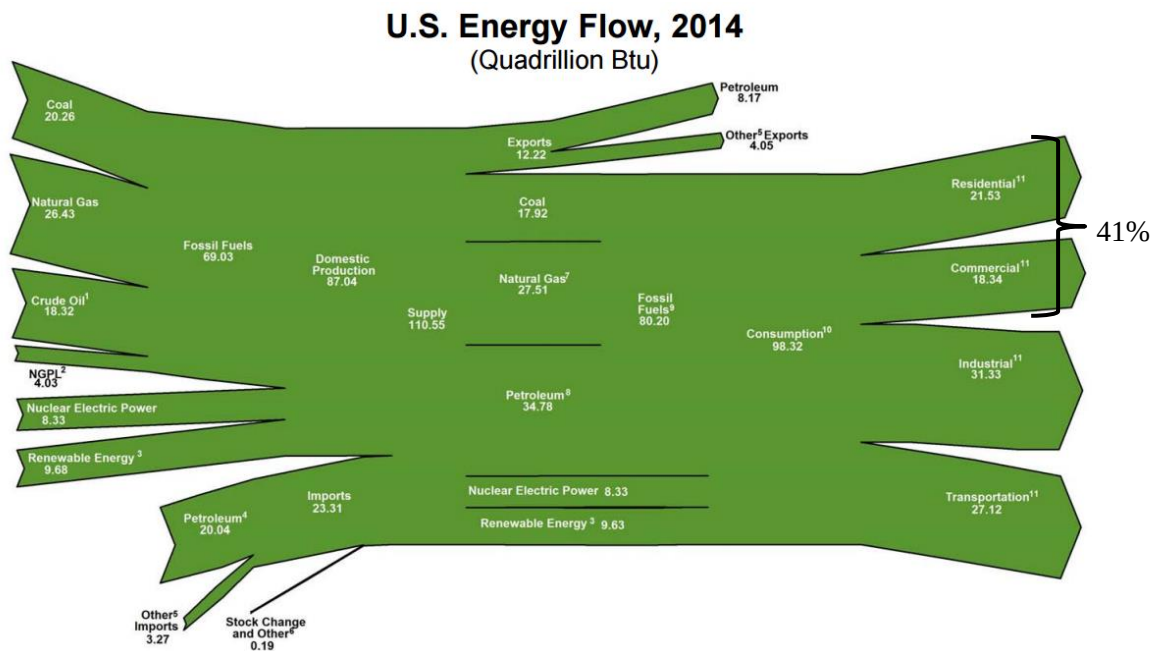
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ABSTRACT

Energy consumption and emission concerns have come to the forefront of political and public attention. The adoption of building energy standards such as ASHRAE Standard 90.1 have helped guide the building industry by setting increasingly stringent building energy performance requirements. In order to meet these ever increasing energy standards, research and development of energy efficient technologies have become a priority. One of these is the unglazed transpired solar collector (UTSC) which is particularly useful in sunny, cold climates such as Bozeman, Montana. This research intends to bridge the gap between theoretical models and field studies by comparing an accepted UTSC model within a commercially available energy modeling software – EnergyPlus – to experimental data collected at Jabs Hall in Bozeman, Montana. An energy model was created to represent a UTSC and its associated building in a commercially available software. Weather and operating data for the UTSC was collected on site. The collected weather data was used to create a custom input weather file for the energy model. The collected operational data was used to characterize the UTSC performance and compare to the energy model results. Limitations for both the energy and data acquisition make it difficult for the results to be compared directly. However, conclusions were drawn about UTSC integration into building systems.

INTRODUCTION

The U.S. Energy Information Administration (EIA) provides independent energy statistics and analysis to the public. Figure 1 is the EIA's energy flow analysis for the United States in 2014, illustrating the distribution of an energy source to the sectors in which the energy was consumed. Buildings, consisting of both residential and commercial sectors, contributed to 41% of the United States' energy consumption in 2014. The EIA predicts that worldwide energy consumption will increase 56% between 2010 and 2040 [1].



¹ Includes lease condensate.

² Natural gas plant liquids.

³ Conventional hydroelectric power, biomass, geothermal, solar/photovoltaic, and wind.

⁴ Crude oil and petroleum products. Includes imports into the Strategic Petroleum Reserve.

⁵ Natural gas, coal, coal coke, biofuels, and electricity.

⁶ Adjustments, losses, and unaccounted for.

⁷ Natural gas only; excludes supplemental gaseous fuels.

⁸ Petroleum products, including natural gas plant liquids, and crude oil burned as fuel.

⁹ Includes -0.02 quadrillion Btu of coal coke net imports.

¹⁰ Includes 0.16 quadrillion Btu of electricity net imports.

¹¹ Total energy consumption, which is the sum of primary energy consumption, electricity retail sales, and electrical system energy losses. Losses are allocated to the end-use sectors in proportion to each sector's share of total electricity retail sales. See Note 1, "Electrical Systems Energy Losses," at the end of U.S. Energy Information Administration, *Monthly Energy Review* (March 2015), Section 2.

Notes: • Data are preliminary. • Values are derived from source data prior to rounding for publication. • Totals may not equal sum of components due to independent rounding.

Sources: U.S. Energy Information Administration, *Monthly Energy Review* (March 2015), Tables 1.1, 1.2, 1.3, 1.4a, 1.4b, and 2.1.

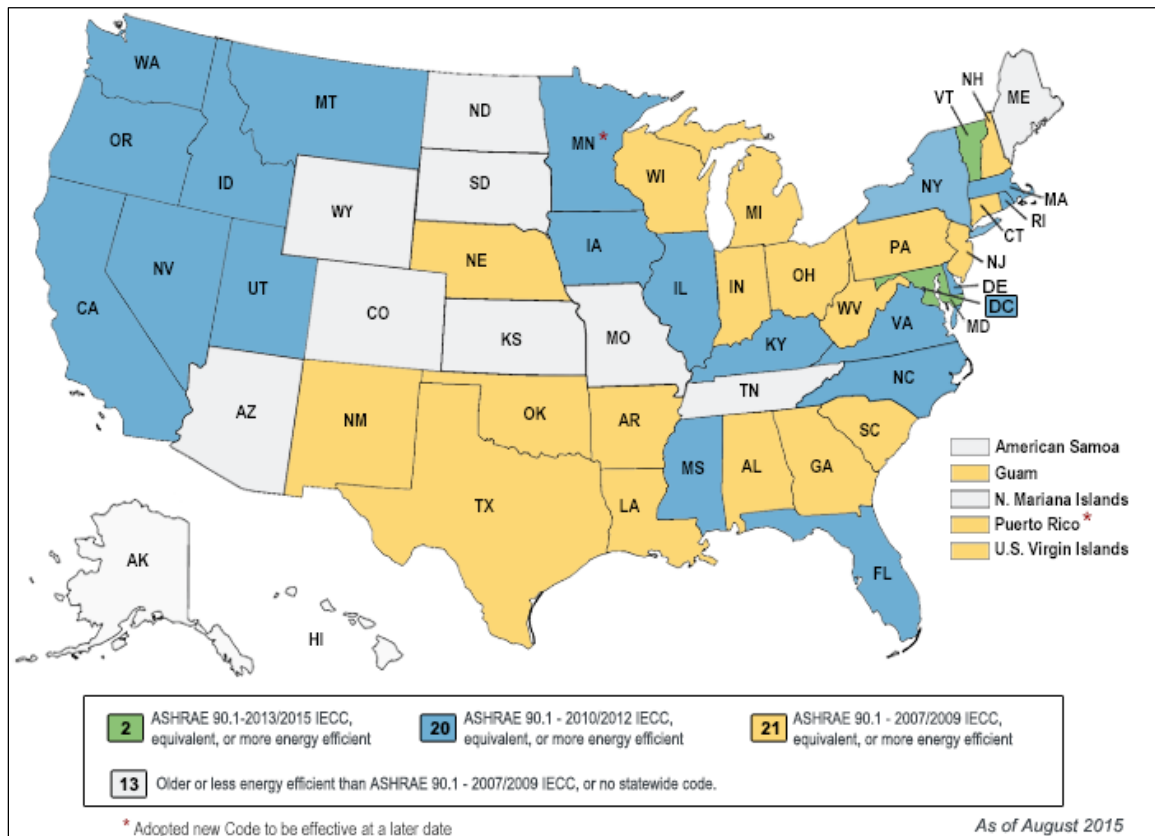
Figure 1: U.S. Energy Flow in 2014, U.S. Energy Information Administration. [2] Noted that residential and commercial building contribute to 41% of the U.S. energy consumption.

Energy Standards

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) has developed an energy standard for commercial buildings called *ANSI/ASHRAE/IES Standard 90.1: Energy Standard for Buildings Except Low-Rise Residential Buildings* (ASHRAE Standard 90.1). ASHRAE Standard 90.1 is continuously updated via addenda and new versions are released every three years. The *International Energy Conservation Code* is another commonly adopted energy code that also has a three year cycle. Each release of an energy code continues to push the envelope in terms of energy efficiency and reduces the standard Energy Use Intensity (EUI) for a commercial building. EUI is a way to compare energy consumption of a building to others and is simply the total energy consumed by a building in a year divided by the building's total area. For instance, ASHRAE Standard 90.1-2007 created a 4.5% reduction from 90.1-2004, 90.1-2010 created an 18.5% reduction from 90.1-2007, and 90.1-2013 created a 6-8% reduction from 90.1-2010 in EUI for commercial buildings [3]. There was a 29-31% reduction in energy consumption for new buildings in nine years from ASHRAE Standard 90.1-2004 to 90.1-2013.

There has also been political response to concerns about rising greenhouse gas (GHG) emissions. According to the White House Press Secretary in March of 2015, the United States is targeting to reduce GHG emissions by 26-28% from 2005 levels by 2025 [4]. The U.S. president's Climate Action Plan [5] lays out key points on helping the country move towards sustainable energy and minimizing the effects of anthropogenic climate change by detailing possible avenues that could be improved. One avenue is

expanding the Better Building Challenge in which commercial and industrial buildings are to be 20% more efficient by 2020 [6]. These national energy efficiency goals set the tone, leading to increased use and adoption of energy codes at the state and municipal level. Figure 2 outlines the status of state adoption of energy codes as of August 2015.



Unglazed Transpired Solar Collector Basics

In order to meet these ever increasing energy standards, research and development of energy efficient technologies and measures have become a priority. One of these is the unglazed transpired solar collector (UTSC). The basic principle of an UTSC is to use solar radiation to passively preheat outside air for a building's fresh air requirement.

Dark-colored, perforated sheet metal – which will be referred to as the UTSC surface – is installed offset of the south façade of a building, creating an air cavity between the sheet metal and building. The UTSC surface absorbs the solar radiation and heats up. To maximized solar absorptivity, the UTSC would be black but can be other dark colors to accommodate the architectural aesthetics of the building. There is an intake duct connecting the air cavity to the building's ventilation system. As seen in Figure 3, outdoor air is slowly drawn through the UTSC surface, absorbing thermal energy, and travels through the cavity to the inlet duct to the building's ventilation system. It should be noted that the UTSC requires a fan to draw air out of the cavity. However, typically the ventilation system fan is sufficient. Therefore, no extra energy is required to use a UTSC, yielding it a passive system.

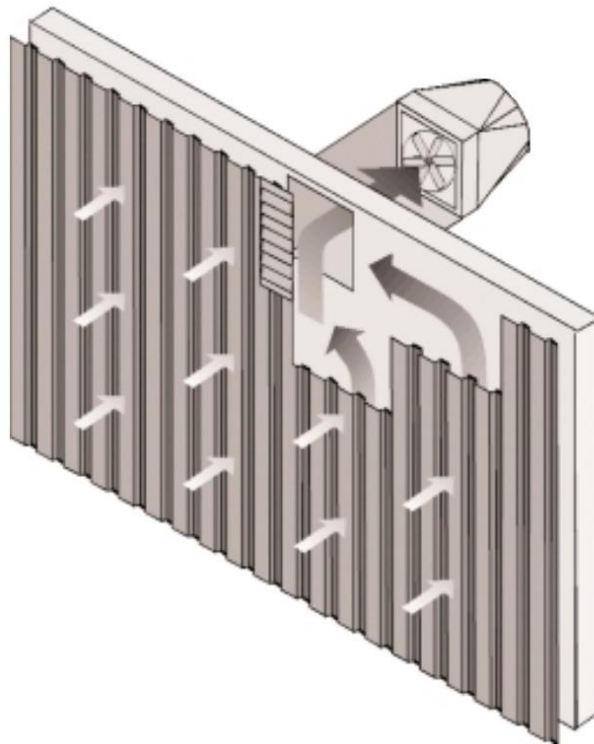


Figure 3: Schematic of a UTSC. [8]

UTSCs provide many benefits to a building and its occupants in cold climates. A UTSC can increase the overall energy efficiency of a building's mechanical system by passively preheating intake air on cold days, reduce emission pollution due to less electrical or fuel consumption, and reduced maintenance expenses over the lifetime of the system. Utilizing intake air preheating yields lower demand on the building's mechanical system and reduces operation costs. A less apparent benefit is the potential to bring additional outdoor air into a building due to the reduced energy cost to heat intake air, increasing the indoor air quality for building occupants. In cold climates conditioning outdoor air is energy intensive; air handling units (AHU's) typically recirculate indoor air to reduce this energy impact. Recirculated air, or commonly referred to as return air, is mixed with a smaller amount of fresh outdoor air. Even though this helps reduce energy consumption, it can have a negative impact on occupant health via increased levels of carbon dioxide and volatile organic compounds in the building. Increased levels of these contaminants decreases occupant comfort and productivity and in extreme cases can lead to what is known as sick building syndrome in which occupants of a building have acute health and comfort effects related to time spent in the building. The Harvard T.H. Chan School of Public Health released a study in October 2015 linking increased ventilation rates and decreased indoor air pollutants with higher cognitive function. In this study occupants working in buildings with enhanced ventilation rates saw 100-300% increase in cognitive function in the domains of crisis response, strategy and information usage.

[9] By using air intake preheating the energy demand to heat outdoor air to a comfortable level is lowered, potentially allowing for more outdoor air intake into a building. Increasing the amount of fresh outdoor air results in improved indoor air quality for

building occupants. With a UTSC preheating outdoor air, it becomes less intensive to condition the air and potentially more could be brought into the building.

Energy Modeling

Computer aided building energy modeling is a powerful design resource. Building energy models are used for evaluation of design decisions, code compliance documentation and more recently for the LEED certification process to compare a design to a code minimum. The United States Green Building Council (USGBC) developed the Leadership in Energy & Environmental Design (LEED) program. LEED is a building certification program that provides metrics to rate energy efficiency and sustainability features of buildings compared to industry standards. One of the metrics in the Energy and Atmosphere category requires an energy model to compare the building design to code minimums outlined by ASHRAE Standard 90.1. The energy model requirement in LEED has increased the use of energy models not only for performance verification of a building but also to inform designers by evaluating options throughout the design process.

History and Evolution of Energy Modeling Tools

The International Building Performance Simulation Association – USA Affiliate (IBPSA – USA) has an overview of the history of building energy modeling in the Building Energy Modeling Body of Knowledge (BEMBook) and some of the key points are outlined below. In the 1970s, both the US Department of Defense (DOD) and the US Department of Energy (DOE) began funding the development of energy modeling

software. The DOD funded the development of Building Loads Analysis and System Thermodynamics (BLAST) program and the DOE funded the development of the simulation tool called DOE-2. [10] Due to the outdated FORTRAN structures, both BLAST and DOE-2 are limited in today's use. [11]

The 1990s brought advancements in computer capabilities and speed, which allowed for improved simulation tools. James J. Hirsch & Associates in collaboration with Lawrence Berkeley National Laboratory (LBNL) and funding from the DOE developed a program that is still used today called the Quick Energy Simulation Tool (eQuest). EQuest, a freeware, utilizes an enhanced version of the DOE-2 as the platform. It integrates wizards and graphics to make building creation, the assessment of energy efficiency measures and reporting of results easier and clearer than previous programs. Around this same time the DOE was developing a new program called EnergyPlus. Elements from both BLAST and DOE-2 were incorporated into EnergyPlus; however there was a substantial change to the framework, making it more modular. This made it easier to update the program and expand its functionality. EnergyPlus is a simulation engine and does not include a graphical user interface (GUI). This has limited its use in industry but is still a valuable tool used by researchers. [10]

In 2009, a new GUI for EnergyPlus was developed by National Renewable Energy Laboratory (NREL) in collaboration with Argonne National Laboratory (ANL), Oak Ridge National Laboratory (ORNL), Pacific Northwest National Laboratory (PNNL) and LBNL. This new GUI known as OpenStudio[®] is written in the Ruby programming language. There is an OpenStudio[®] plug-in for SketchUp, a 3D modeling software, which allows the building geometry to be quickly drawn. Space types and construction sets can

be applied to the drawn spaces in either the SketchUp plug-in or OpenStudio® itself. The ability to use computer aided drafting as opposed to manually inputting surface dimensions is ideal for rapid parametric analysis and testing the effect of building geometry on the overall energy performance. OpenStudio® is still a relatively new program and not all the functionality and building elements of EnergyPlus are incorporated, including the UTSC. However, this continues to improve with every release, incorporating new features and building objects.

Jabs Hall

In October of 2011, Montana State University alumnus Jake Jabs donated 25 million dollars to the College of Business. Part of this donation was used to build Jabs Hall, the new home of the Jake Jabs College of Business & Entrepreneurship. The building construction was completed in 2015 and the grand opening ceremony was May 7th, 2015. The entire building is 4722 m² (50,830 ft²) and split across four floors it has classrooms on the south side, offices on the north side, a large open lobby, a café on the first floor, and tables and couches peppered throughout for studying. Jabs Hall received LEED Gold certification and has many energy efficient and sustainable features. One of the features is the UTSC on the south wall of the rooftop mechanical penthouse. Figure 4 is a photo of the south side of Jabs Hall. The UTSC is the black surface on the top floor and is used for the research discussed in this document.



Figure 4: View of the south side of Jabs Hall. UTSC is highlighted in above image.

Bozeman, MT Weather Overview

Montana State University (MSU) and Jabs Hall – the location of this research – are located in Bozeman, Montana. Bozeman’s climate usually consists of a short mild summer and a long cold winter. There are many sunny days in Bozeman year long. This primarily heating driven climate along with a large amount of solar energy exposure makes Bozeman an ideal location for UTSC. There is a weather station on the top of Cobleigh Hall which has a significant archive of weather data. A year of weather data from September 25, 2014 to September 24, 2015 was used from the Cobleigh Hall weather station archive to create weather bin sets for temperature, wind speed, wind direction and solar radiation. [12] Due to the configuration of the HVAC system at Jabs Hall, which will be discussed later, the temperature must be below 12.8°C (55°F) in order to have the possibility of utilizing the UTSC. Figure 5 is the hourly temperature at

Cobleigh Hall for an entire year. The temperatures are broken up into bins for every 20°F.

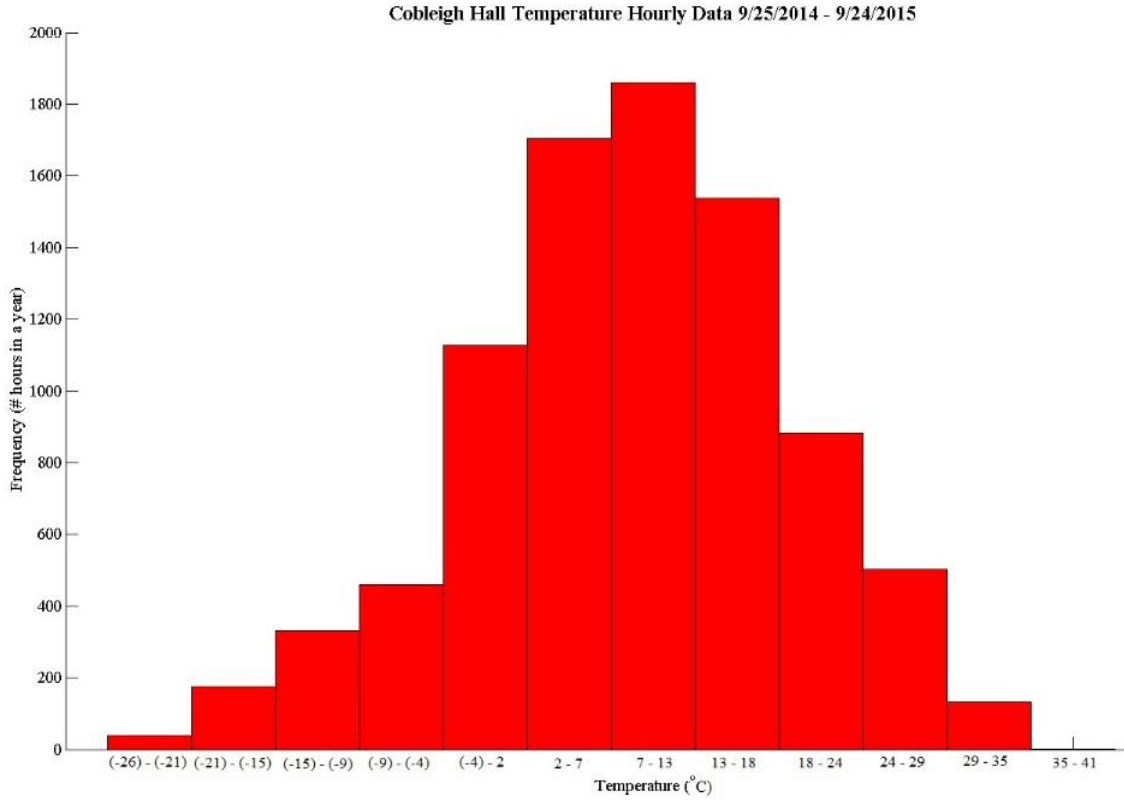


Figure 5: Hourly binned temperature data at Cobleigh Hall in Bozeman, MT.

Solar radiation typically ranges from $0 - 1000 \frac{W}{m^2}$ ($0 - 317 \frac{Btu}{h \cdot ft^2}$), where $0 \frac{W}{m^2}$ ($0 \frac{Btu}{h \cdot ft^2}$) is complete darkness and $1000 \frac{W}{m^2}$ ($317 \frac{Btu}{h \cdot ft^2}$) is a sunny day with no solar obstructions such as clouds. Figure 6 shows binned solar radiation data for a year at Cobleigh Hall, not including night hours or $0 \frac{W}{m^2}$ ($0 \frac{Btu}{h \cdot ft^2}$).

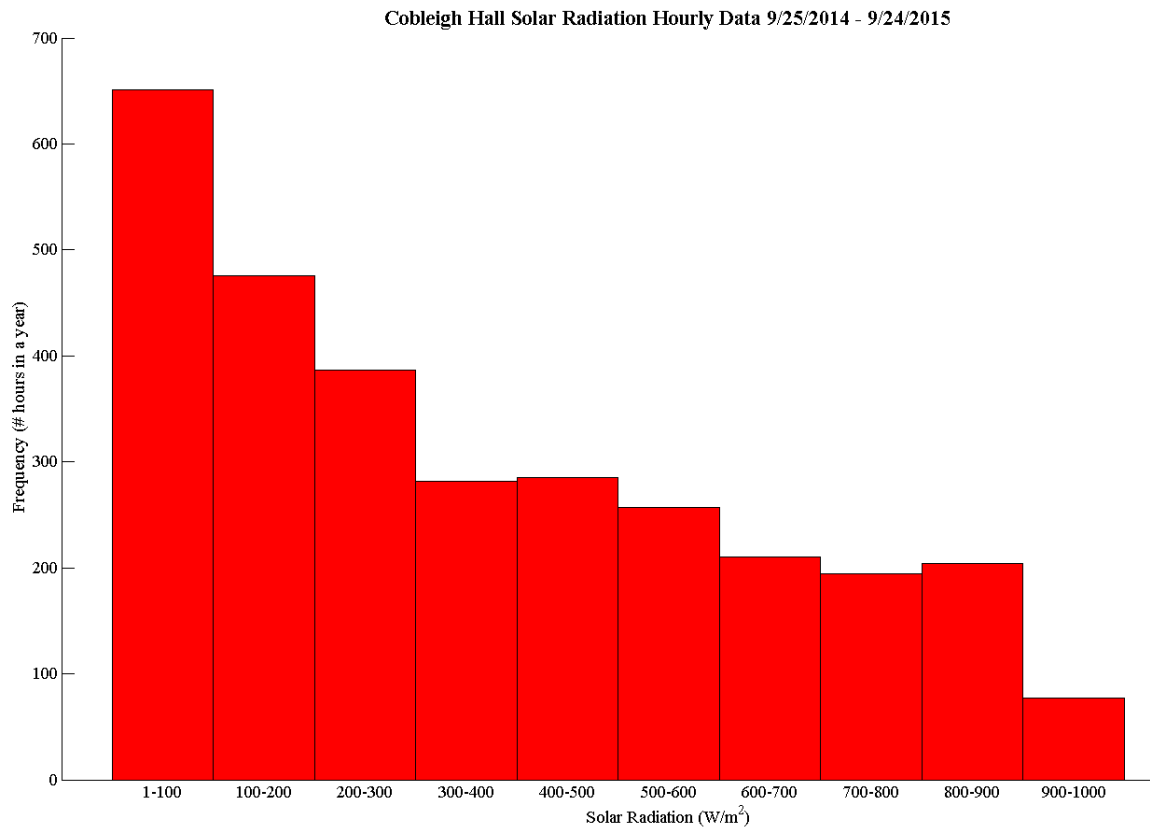


Figure 6: Hourly binned solar radiation data, not including zero values, at Cobleigh Hall in Bozeman, MT.

Figure 7 is a wind rose for Cobleigh Hall and includes both wind speed and direction on one graphic. The wind rose shows the frequency, in percentage, that the wind speed falls in a certain range for that particular direction. The wind speeds are grouped into bins of 1 m/s (2.2 mph) and wind direction is grouped into bins of 10 degrees where zero degrees is northern winds. From all of these charts it is clear to see that the weather in Bozeman, MT is ideal for a UTSC; there are many cold and sunny days in the year. There are also occasional high wind speeds which is of interest for validation of the UTSC model.

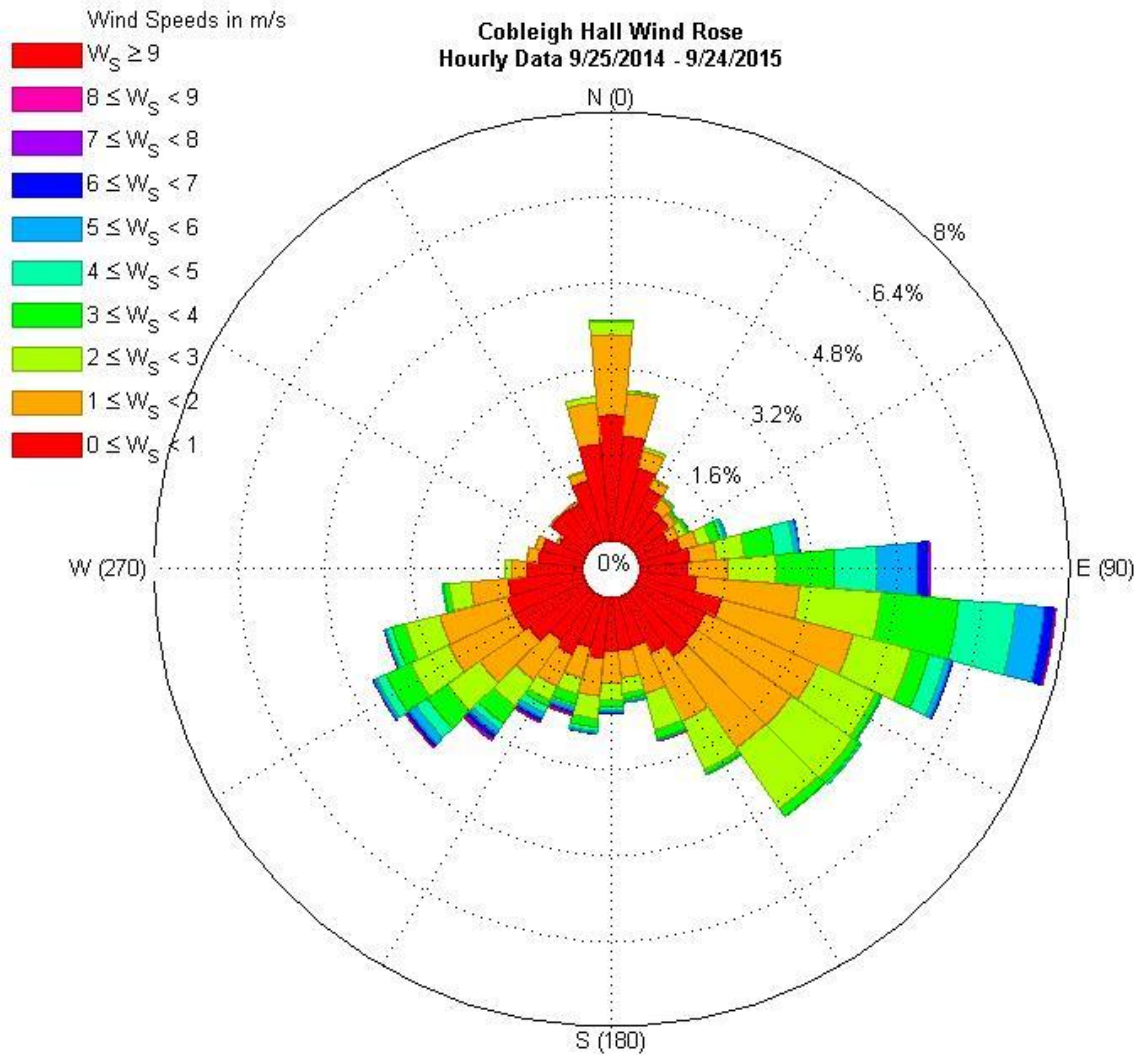


Figure 7: Wind Rose for Cobleigh Hall in Bozeman, MT.

Purpose

The US DOE released a Federal Technology Alert about UTSC in 1998. A statement was made about implementation barriers in which UTSC and other solar technologies have been stigmatized after many poorly designed and performing systems were installed during the expansion of the solar market in the 1970s. [8] Since then, there have been many field studies and models developed for UTSC. This research intends to

bridge the gap between theoretical models and field studies by comparing an accepted UTSC model within an energy modeling software – EnergyPlus – to experimental data collected at Jabs Hall in Bozeman, Montana. This thesis will:

- 1) Overview fundamental information about UTSC found in literature, including models and previous field studies, and how these are applied into current building energy modeling software.
- 2) Highlight the UTSC studied at MSU and the data acquisition scheme.
- 3) Review the EnergyPlus model of the experimental UTSC and building.
- 4) Detail the experimental results – including raw data collected, effectiveness calculations and thermography studies – and the simulated results from the EnergyPlus model.
- 5) Compare the collected and modeled data and draw conclusions from this.

BACKGROUND

Over the past quarter century, dozens of peer reviewed journal articles have been published relating to UTSC. They include mathematical models coupled with small scale experiments, field studies, computational fluid dynamics models and parametric studies. All of these have a slightly different approach to the problem and draw conclusions on the performance of UTSC. Shukla et al. [13] provides an overview of these journal articles as of 2012, summarizing the approach taken and findings. For the purposes of this paper, the background section will focus on two of these mathematical models that are tied to small scale experiments – Kutscher [14] and Van Decker et al. [15] – and how these mathematical models are incorporated into an energy modeling program called EnergyPlus.

Kutscher [14]

Kutscher studied the convective heat transfer effectiveness, or heat exchange effectiveness, of unglazed transpired solar collectors. The heat exchange effectiveness is the heat transferred to the air over the maximum possible heat transfer, which is when the air is the same temperature as the UTSC plate surface. This relationship is shown in Equation (1) where ϵ_{HX} is the heat exchange effectiveness, T_o is the outlet air temperature, T_{amb} is the ambient air temperature and T_s is the surface temperature of the UTSC.

$$\epsilon_{HX} = \frac{T_o - T_{amb}}{T_s - T_{amb}} \quad (1)$$

Kutscher experimentally derived a correlation for the Nusselt number for air flow through an UTSC. This correlation can be used to predict heat exchange effectiveness of an UTSC within $\pm 9\%$.

In the Kutscher small scale experiment $0.3 \text{ m} \times 0.5 \text{ m} \times 0.0008 \text{ m}$ (11.8 in $\times$ 19.7 in $\times$ 0.03125 in) perforated aluminum plates were tested. Due to the experimental set up, suction flow rates, cross flow (wind) velocities and radiation could be controlled. Due to how thin the test plates were, the surface temperature of the plates were constant or isothermal throughout the experiment. Plate porosity was varied with values ranging from 0.1% to 5%. A dimensionless term σ was defined to express porosity in later experimentally derived correlations. Equation (2) defines the dimensionless porosity term σ where A is the plate surface excluding the holes and A' is the total plate area including the holes.

$$\frac{A}{A'} = 1 - \sigma \quad (2)$$

All test plates had holes in a triangular layout. The suction flow rates varied from $0.02 - 0.07 \frac{\text{kg}}{\text{m}^2 \cdot \text{s}}$ ($3.7 - 13.3 \frac{\text{ft}}{\text{min}}$ at typical operating condition in Bozeman, MT) and crosswind speeds ranged from 0 to 4 m/s (0 to 9 mph). For each test condition, the ambient, surface, and outlet temperatures were directly measured and the effectiveness were calculated using Equation (1).

The Nusselt number (Nu) is a dimensionless quantity describing the ratio of convective to conductive heat transfer across a boundary and is calculated by the heat transfer coefficient multiplied by an appropriate length term divided by the thermal

conductivity, Equation (3). In this case the length term is D , the hole diameter, and k is the thermal conductivity of the air.

$$Nu_D = \frac{UD}{k} \quad (3)$$

The experimentally derived correlation for the Nusselt number – Equation (4) – takes into account the physical properties of the UTSC and conditions experienced. This includes hole pitch (P), hole diameter (D), porosity (σ), wind speed (U_∞) average suction velocity across the front of the plate (V), and Reynolds number (Re) through the holes – Equation (5) where V_h is the air velocity through the holes and ν is the kinematic viscosity of the air. As previously stated this Nusselt number correlation can be used to predict the heat exchange values within $\pm 9\%$ for porosities of 0.1-5% and Reynolds numbers of 100-2000.

$$Nu_D = 2.75 \left[\left(\frac{P}{D} \right)^{-1.2} - Re_D^{0.43} + 0.011\sigma Re_D \left(\frac{U_\infty}{V} \right)^{0.48} \right] \quad (4)$$

$$Re_D = \frac{V_h D}{\nu} \quad (5)$$

Then the heat transfer coefficient U was determined in the Nusselt number definition previously shown in Equation (3). Once U is solved for, the heat exchange effectiveness can be determined from the relationship expressed in Equation (6) where C_p is the specific heat capacity of the air and $\dot{m}$ is the mass flow rate of the air.

$$\epsilon_{HX} = 1 - e^{-\frac{UA}{\dot{m}C_p}} \quad (6)$$

Overall, the experiment revealed that the heat exchange effectiveness improved with increasing wind speed and decreasing suction flow rates, hole pitch and hole diameter.

Van Decker et al. [15]

Van Decker et al. introduced a new model to predict effectiveness that breaks it down into three heat transfer contributions from the front of the plate, through the holes, and the back of the plate. Similarly to Kutscher, the correlation created was fit to experimental data. However, unlike Kutscher – who created a correlation for the Nusselt number that then could be related to heat exchange effectiveness – Van Decker et al. created a correlation for effectiveness directly.

The experiment tested various plates in a controlled environment. All test plates were of the dimensions 0.6 m x 0.6 m (23.6 in x 23.6 in) with varying thickness and materials. Aluminum, stainless steel, and PVC plates were tested with square hole layouts. One aluminum plate had a triangular hole layout and was identical to one of the plates tested in Kutscher so the results from both studies could be compared. The test apparatus allowed for radiation, suction velocity and wind speed to be controlled. The wind velocity was varied from 0 to 5.0 m/s (0 - 11.2 mph) and the suction velocity from 0.028 to 0.083 m/s (5.5 – 16.3 ft/min). 50 thermocouples were fixed to the test plates so the average plate temperature could be determined.

Results from the tests indicate that effectiveness increased with decreasing suction velocity, hole pitch, and hole diameter and effectiveness also improved with increasing plate thickness. Hole pitch and suction speed had the largest effect on effectiveness while thermal conductivity of the plate had the smallest effect on effectiveness. When comparing the parameters that were also tested by Kutscher, the findings were consistent. The isothermal behavior of the plates was also tested. The largest temperature variation

occurred in the PVC plate of $\pm 2.5^{\circ}\text{C}$ (4.5°F). In the metallic plates, the temperature variation was negligible. Two plates had identical characteristics except for their hole layout. It was determined that the triangular hole layout performed slightly better than the square hole layout and that a pitch scaling factor of 1.6 could be applied to the Kutscher correlation to accommodate a square hole layout. It was also concluded that the largest variation between the Kutscher correlation and this experimental data was due to plate thickness. From this it was determined that a new correlation for effectiveness was required that accommodates more UTSC characteristics and accounts for the heat transfer mechanisms in the front of the plate, through the holes, and on the back of the plate.

The effectiveness correlation developed assumed that all the plates were isothermal but there was discussion on how to account for non-isothermal plates. Radiation heat transfer coefficients are non-linearly related to surface and ambient temperatures however, a common assumption over small delta temperature ranges – such as 10°C to 30°C (18°F to 54°F) – is to treat the radiant heat transfer coefficient constant. Once this is assumed it can be shown that the surface temperature is a function of the point surface temperatures as shown in Equation (7) where T_p is the average plate surface temperature, T'_p is the temperature at a point of the plate of the A_{rep} or the surface area representative of the plate.

$$T_p = \iint_{A_{rep}} T'_p(x, y) dA \quad (7)$$

In this effectiveness correlation the heat transfer contribution is broken down into three parts: front of the plate, the holes, and back of the plate. An effectiveness value correlation was developed for each separately and then combined into one.

The heat transfer mechanism at the back of the plate is described as a jet that breaks into eddies, or separated flow. For separated flow it can be shown that the effectiveness is correlated to the Stanton number and then to the Reynolds number. This was based on the assumptions that there is no external wind or that the wind would have little impact on the heat transfer characteristics for two reasons. First, that the downward momentum of the wind experienced by the jet through the hole would be small. Second, that expected wind speeds would be smaller or similar to that experienced in the hole.

The heat transfer mechanism on the front of the plate was related to two Reynolds numbers, based on the wind speed and suction velocity. This relationship, correlated well with windy conditions, but yielded an effectiveness value of zero in conditions without wind. So a correlation from Arulanandam et al. [16] – a previous CFD model of transpired solar collectors at zero wind conditions – was used for the zero wind condition and a maximum function is used to insure that one of the two relations is used in the effectiveness calculation.

For the heat transfer mechanism through the hole, laminar flow is assumed because the experimental Reynolds numbers at this location were found to be less than 2000. Developing flow in a cylinder yields an effectiveness relationship. However, this relationship did not correlate as well as expected because the air temperature entering the hole was non-uniform. A parameter relating the geometry of the hole was added to improve the fit of the data.

Combining these three terms and performing a global fit of the effectiveness correlation yielded in Equation (8) where P is the hole pitch, D is the hole diameter, t is the thickness and the Reynolds numbers represented by Equation (9) through Equation

(12). In these Reynolds numbers relationships V_s is the suction velocity, U_w is the wind speed, ν is the kinematic viscosity, P is the hole pitch, D is the hole diameter and σ is the porosity.

$$\epsilon = \left[1 - \left(1 + Re_s \max[1.733 Re_w^{-1/2}, 0.02136] \right)^{-1} \right] \times \left[1 - \left(1 + 0.2273 Re_b^{1/2} \right)^{-1} \right] \quad (8)$$

$$\times \exp \left(-0.01895 \frac{P}{D} - \frac{20.62}{Re_h} \frac{t}{D} \right)$$

$$Re_s = \frac{V_s P}{\nu} \quad (9)$$

$$Re_w = \frac{U_w P}{\nu} \quad (10)$$

$$Re_b = \frac{V_s P}{\nu \sigma} \quad (11)$$

$$Re_h = \frac{V_s D}{\nu \sigma} \quad (12)$$

The effectiveness formulation expressed in Equation (8) when compared directly to that of Kutscher had excellent agreement. It was concluded that 62% of the air temperature gain occurred at the front of the plate, 28% occurred in the holes and 10% occurred at the back of the plate. Experimental data validates the model over the following parameters: suction velocity from 0.028 to 0.083 m/s (0 – 5.5 fpm), wind speed from 0 to 5 m/s (0 – 11.2 mph), hole pitch from 7 to 24 mm (0.28 – 0.95 in), hole diameter 0.8 to 3.6 mm (0.032 – 0.14 in), plate thickness from 0.6 to 6.5 mm (0.024 – 0.26 in) and thermal conductivities ranging from 15 – 200 $\frac{W}{m \cdot K}$ $\left(0.087 - 120 \frac{Btu}{h \cdot ft \cdot ^\circ F} \right)$.

EnergyPlus Model of UTSC [17]

There is a UTSC model component in EnergyPlus that is not yet available in OpenStudio. The UTSC model impacts both the envelope of the building and the HVAC air loop in the energy model as it is attached on the outside of the specified heat transfer surface (building wall) and is connected to the outdoor air path. Simply put, the UTSC component determines how much to increase the outdoor air temp entering the building's air loop and modifies the heat transfer through the building at that location. There are two conditions in which the UTSC operates, the first is when it is “off” or is “bypassed” and the second is when it is “on” or is “active”. In bypass mode, there is no air forced through the UTSC, acting as a radiation and convection baffle. In active mode, there is an assumed uniform suction velocity across the UTSC. The heat exchange effectiveness of the UTSC is used to determine the air temperature leaving the UTSC. There are two correlations that EnergyPlus uses to determine the USTC heat exchanger effectiveness, the Kutcher Correlation (1994) and the VanDecker et al. Correlation (2001). Both correlations were detailed earlier in the chapter, however the EnergyPlus nomenclature and how EnergyPlus uses the correlations are outlined below.

EnergyPlus Nomenclature

A	Area, UTSC (m^2)
c_p	Specific heat, air, constant pressure (J/kg K)
D	Hole diameter (m)
I_{sc}	Incident solar radiation, total (W/m^2)
k	Thermal conductivity, air (W/m K)

$\dot{m}$	Suction mass flow rate, air (kg/s)
P	Pitch or distance between holes (m)
t	UTSC thickness (m)
$T_{a,HX}$	Temperature, air, leaving the UTSC, entering the plenum (°C)
T_{amb}	Temperature, air, ambient (°C)
$T_{a,plen}$	Temperature, air, leaving the plenum, entering the outdoor air system (°C)
$T_{s,coll}$	Temperature, UTSC (°C)
U	Overall heat transfer coefficient (W/m ² K)
U_{∞}	Velocity, wind (m/s)
V_h	Velocity, air, through the holes (m/s)
V_s	Velocity, air, average suction across UTSC (m/s)
ϵ_{HX}	Heat exchange effectiveness (decimal format)
ν	Kinematic velocity, air (m ² /s)
σ	Porosity, area fraction of the holes (dimensionless)
η	Efficiency (decimal format)

Reynolds Numbers

There are four Reynolds Number formulations that EnergyPlus uses when determining the effectiveness of a UTSC: the Kutcher Correlation uses one and the Van Decker et al. Correlation uses all four. The Reynolds number shown in Equation (13) is used in both the Kutcher Correlation and Van Decker et al. Correlation. It is related to the air flow through the holes.

$$Re_D = \frac{V_h D}{\nu} \quad (13)$$

The Reynolds number based on the suction velocity shown in Equation (14) and the Reynolds number based on wind velocity in Equation (15) are used when determining the heat transfer for the front of the plate in the Van Decker et al. Correlation.

$$Re_s = \frac{V_s P}{\nu} \quad (14)$$

$$Re_w = \frac{U_\infty P}{\nu} \quad (15)$$

A Reynolds number based on the hole velocity – Equation (16) – is used when determining the heat transfer behind the plate in the Van Decker et al. Correlation.

$$Re_b = \frac{V_h P}{\nu} \quad (16)$$

Kutcher Correlation

The Kutcher Correlation takes into account the heat transfer due to the outside air on the front of the UTSC, the air as it passes through the holes, and the air as it interacts with the back of the UTSC. This is determined using only a single Reynolds number which is based on the diameter of the holes and the velocity of the air passing through the holes. It can be seen that this correlation, Equation (17), depends on the above discussed Reynolds number, hole pitch, hole diameter, porosity, wind, and velocity through the holes. Porosity is the dimensionless area fraction of the holes as previously defined in Equation (2).

$$Nu_D = 2.75 \left[\left(\frac{P}{D} \right)^{-1.2} Re_D^{0.43} + 0.011 \sigma Re_D \left(\frac{U_\infty}{V_h} \right)^{0.48} \right] \quad (17)$$

The Nusselt number is then related to the overall heat transfer coefficient as seen in Equation (18). Once the overall heat transfer coefficient is known, the heat exchange effectiveness can then be determined using Equation (19).

$$Nu_D = \frac{UD}{k} \quad (18)$$

$$\epsilon_{HX} = 1 - e^{-\frac{UA}{\dot{m}C_p}} \quad (19)$$

The same limitations discussed in the Kutscher (1994) section of this chapter apply to this model. One limitation has since been addressed. The Kutscher Correlation was developed for triangular hole configuration, however based on the results from Van Decker et al. (2001), P can be scaled in EnergyPlus to allowed for a square hole configuration. This scaling factor is 1.6.

Van Decker et al. Correlation

As discussed in the Van Decker et al. (2001) the Van Decker et al. Correlation extends the Kutscher Correlation to include a wider range of UTSC parameters. Square hole configuration and UTSC thickness are two of these. Equation (20) is the heat exchange effectiveness.

$$\begin{aligned} \epsilon_{HX} = & \left[1 - \left(1 + Re_s \text{Max}(1.733Re_w^{-1/2}, 0.02136)^{-1} \right) \right] \\ & \times \left[1 - \left(1 + 0.2273Re_b^{1/2} \right)^{-1} \right] \times e^{\left(-0.01895 \frac{P}{D} - \frac{20.62t}{Re_D D} \right)} \end{aligned} \quad (20)$$

Heat Exchanger Leaving Temperature

Once either the Kutscher Correlation or the Van Decker et al. Correlation is used to solve for the heat exchange effectiveness, the temperature of the air leaving the UTSC plate and entering the plenum can be found. Equation (21) can be rearranged to solve for this temperature.

$$\epsilon_{HX} = \frac{T_{a,HX} - T_{amb}}{T_{s,coll} - T_{amb}} \quad (21)$$

UTSC Heat Balance

One assumption made by the model is that the UTSC is thin and conductive enough to model as a single temperature ($T_{s,coll}$) on both sides and over the entire area. The control volume heat balance approach is applied to the UTSC surface. This heat balance is shown in Figure 8 for both bypass and active modes.

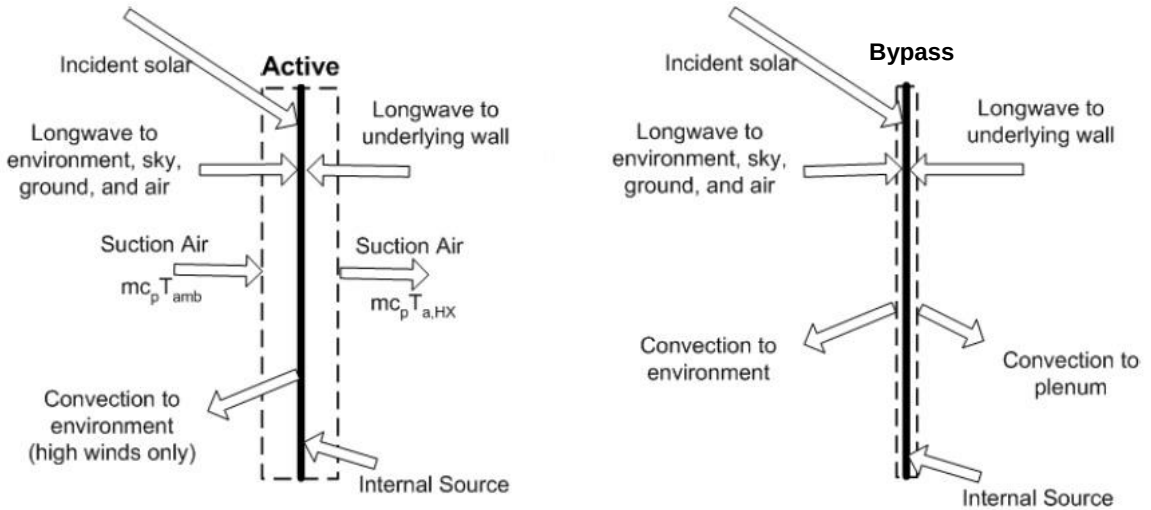


Figure 8: Control Volume Heat Balance of UTSC Surface [17]

Each of the components expressed in Figure 8 are a parameter in the heat flux balance equation. From this the UTSC surface temperature is determined for both the passive and active cases.

UTSC Plenum Heat Balance

The plenum is the air cavity between the surface of the UTSC and the building skin. The air in the plenum is assumed to be well mixed. The temperature of the air in the plenum ($T_{a,plen}$) is found by creating a control volume heat balance on the plenum. This heat balance is shown in Figure 9 for both bypass and active modes.

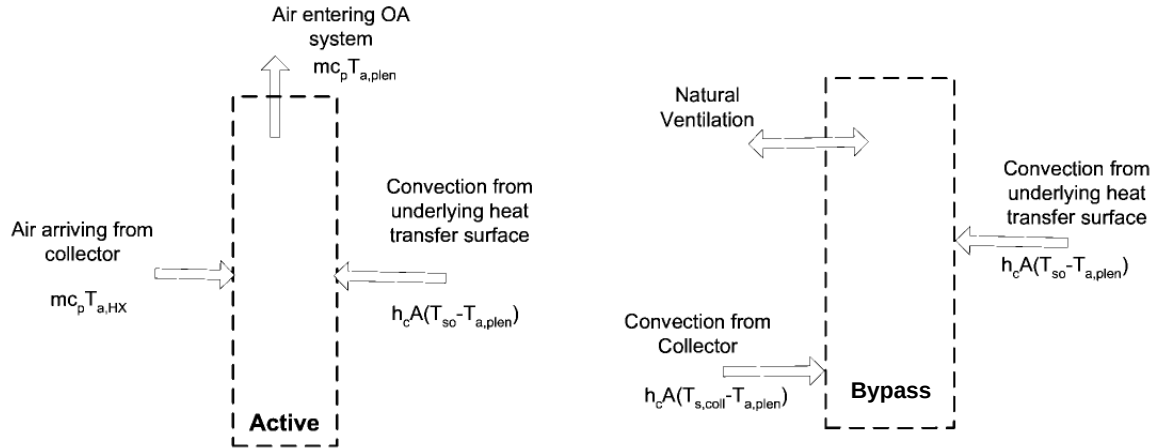


Figure 9: Control Volume Heat Balance of UTSC Plenum [17]

System Efficiency

Efficiency, as related to a UTSC, is defined as the ratio of useful heat gain to the total incident solar radiation on the surface area of the collector. There are two efficiencies that can be determined: overall and collector. The overall efficiency is defined in Equation (22) and the collector efficiency in Equation (23).

$$\eta = \frac{\dot{m}c_p(T_{a,plen} - T_{amb})}{I_{sc}A} \quad (22)$$

$$\eta = \frac{\dot{m}c_p(T_{a,HX} - T_{amb})}{I_{sc}A} \quad (23)$$

EXPERIMENTAL DATA

Jabs Hall UTSC

The UTSC installed on the south wall of the rooftop mechanical penthouse of Jabs Hall is 20.14 m (66 ft 1 in) long and 3.96 m (13 ft) tall. There is a 0.20 m (8 in) deep air cavity between collector plate and the penthouse wall. On the east side of the wall is the inlet duct to the air handling unit (AHU). The inlet AHU duct measures 0.6 m by 0.9 m (24 in x 36 in) in cross section. A weather station is located above the UTSC on the left or west edge of the wall. Figure 10 is a photo of the Jabs Hall UTSC and weather station.

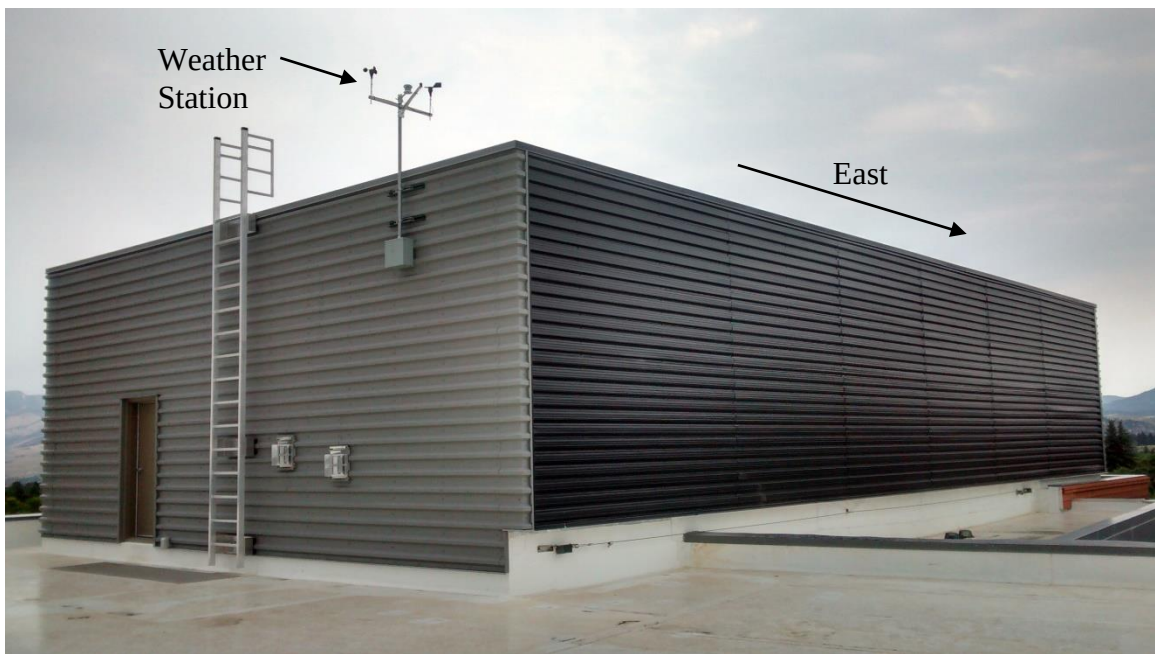


Figure 10: Jabs Hall UTSC and weather station.

As seen in Figure 10, the UTSC is not a flat collector plate but a corrugated plate. The corrugation profile, seen in Figure 11, increases the area available for heat transfer without increasing the overall area of the wall.

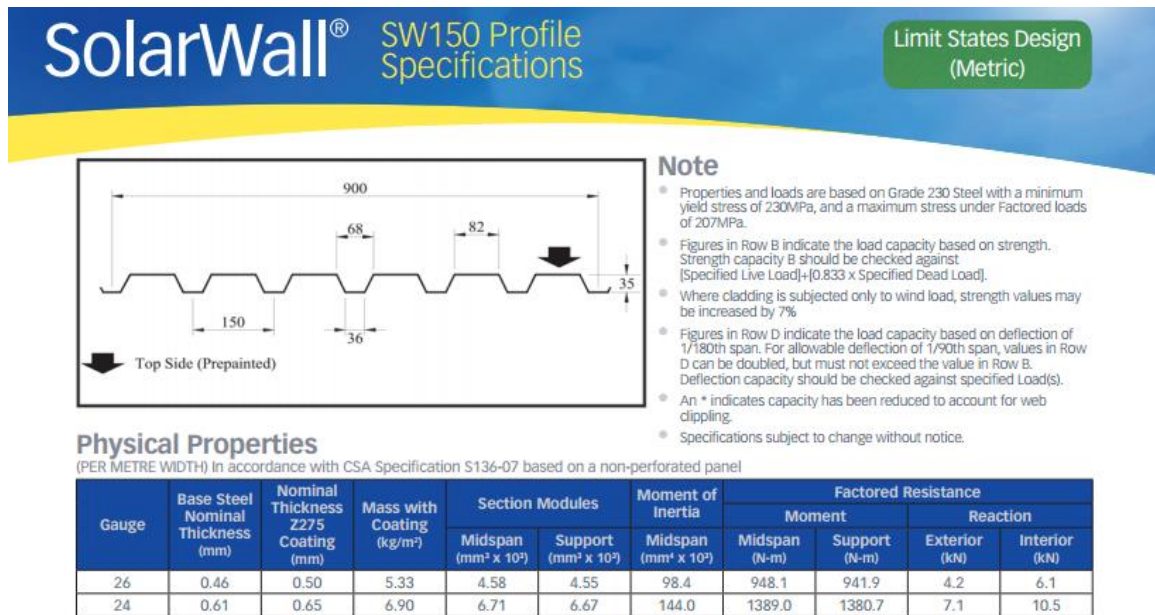


Figure 11: Jabs Hall UTSC specification sheet illustrating the profile. [18]



Figure 12: Jabs Hall UTSC hole layout.

The holes in the Jabs Hall UTSC are not circular as assumed by models in literature. The holes, shown in Figure 12, are slits punched into the plate. The pitch, or distance between the center points of two holes, varies along the profile of the collector as well. The pitch is shorter on the flat section of the plate and is longer along the bends.

To account for this in the energy model, an averaged diameter of the hole will be used. The area of a slit was measured and the diameter of a circle with equivalent area was determined. The different pitches were measured and a weighted average of the pitches will be used in the model.

One other factor to the performance of UTSC is the location of objects that cast shadows on it. The Jabs Hall grounds has a tight cluster of three trees southeast of the UTSC. These trees can be seen in Figure 13, giving a perspective as to when these trees would cast shadows on the UTSC. This was of particular concern during the winter months when the sun angle is low and the demand for preheating intake air is high.

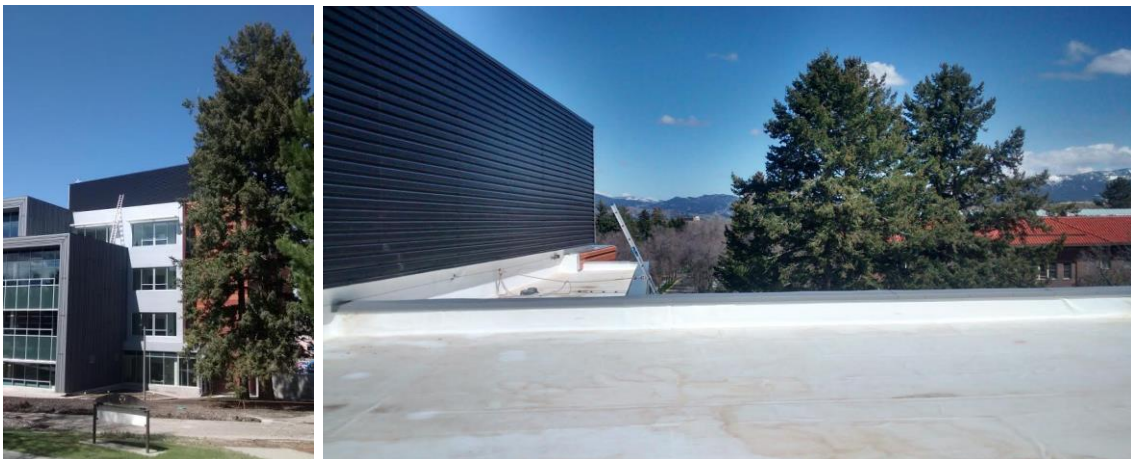


Figure 13: Left - A view of the trees and Jabs Hall UTSC from the southeast. Right - A view of the same trees from the west side of the roof.

A solar availability study was performed. Two points were analyzed, both of which were in the center of the UTSC in the horizontal direction. The first at the bottom of the UTSC in the vertical direction and the second was at the top of the UTSC in the vertical direction. It was found that the cluster of trees created a significant solar disruption from

September to March. In the months of November to February the shadow would be cast over the entire vertical direction of the UTSC.

Data Acquisition

In order to characterize the performance of the Jabs Hall UTSC, sensors were installed in various locations of interest. There was a weather station installed above and on the west side of the UTSC as previously seen in Figure 10. The weather station consisted of an anemometer that measures the wind and gust speeds, a wind vein that measures the wind direction, a shielded temperature sensor that measures outdoor air temperature, relative humidity and dew point, and silicon pyrometer that measures the global solar irradiation. There are six thermocouples in a grid pattern on the surface of the UTSC and six temperature sensors four inches directly behind the thermocouples in the cavity. Figure 14 shows the location of the surface sensors (S), cavity sensors (C) and inlet duct. There are sensors located in the inlet duct into the air handling unit (AHU). There is a velocity sensor and temperature sensor that measures temperature, relative humidity and dew point of the air leaving the UTSC and entering the AHU. All this information depicts the weather conditions affecting the UTSC, the temperature profile of the surface and in the cavity of the UTSC, and the amount of air and its temperature leaving the UTSC and entering the AHU.

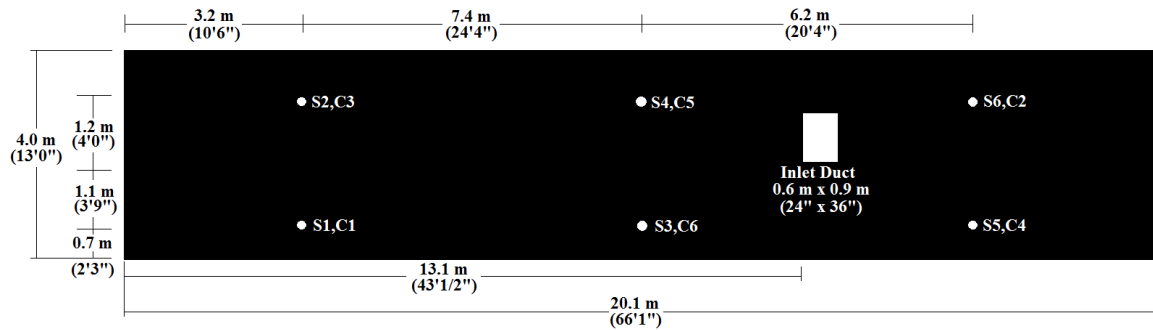


Figure 14: Location of surface sensors (S), cavity sensors (C) and inlet duct on the Jabs Hall UTSC

Onset's HOBO® data loggers and weather station sensors were selected for the data acquisition of the Jabs Hall UTSC. Two HOBO® U30 Ethernet data loggers were required to accommodate all the sensors required. The Ethernet data loggers can be accessed and controlled remotely via the internet; the collected data is automatically sent to an email or FTP site based on user settings. These features were important for long term data collection purposes. Onset has sensors and weather station components specifically designed for these data loggers. The weather station sensors – wind speed, wind direction, solar radiation, temperature and relative humidity – are all Onset sensors. The cavity temperature sensors, velocity sensor located in the inlet duct and temperature sensor located in the duct are also Onset sensors. The surface temperature sensors are T-type thermocouple wires and must receive signal conditioning in order to be collected by the HOBO® data loggers. Onset has a 4-20 mA input adapter sensor, so the T-type thermocouple signal was converted to 4-20 mA signal using an Omega temperature transmitter. Provided user input regarding thermocouple wire type and input temperature ranges, the Omega temperature transmitter converts the thermocouple voltage to a 4-20 mA signal accepted by the Onset sensor. Table 1 and Table 2 list the sensors for each of

the data loggers, their outputs, and the location of each sensor. The data loggers are programmed to take data every 5 minutes. All the sensor specification sheets are located in Appendix E.

Table 1: Sensor list for the "weather station" data logger (HOBO® U30 ETH S/N 10459859)

Sensor Name	Onset Product Number	Serial Number	Channel Output	Sensor Location
Wind Direction Smart Sensor	S-WDA-M003	10542537	Wind Direction (°) where North = 0°	Weather Station
Wind Speed Smart Sensor	S-WSA-M003	10542556	Wind Speed (mph) Gust Speed (mph)	Weather Station
Temperature/RH Smart Sensor	S-TBH-M00x	10544610	Temperature (°F) Relative Humidity (%) Dew Point (°F)	Weather Station
Silicon Pyranometer Smart Sensor	S-LIB-M003	10704746	Global Solar Irradiation (W/m ²)	Weather Station
12-Bit 4-20mA Input Adapter	S-CIA-CM14	10737491	Calibrated Temperature (°F) originating from T-type thermocouple	Surface Temp. 1
12-Bit 4-20mA Input Adapter	S-CIA-CM14	10737492	Calibrated Temperature (°F) originating from T-type thermocouple	Surface Temp. 2
12-Bit 4-20mA Input Adapter	S-CIA-CM14	10737493	Calibrated Temperature (°F) originating from T-type thermocouple	Surface Temp. 3
12-Bit 4-20mA Input Adapter	S-CIA-CM14	10737494	Calibrated Temperature (°F) originating from T-type thermocouple	Surface Temp. 4
12-Bit 4-20mA Input Adapter	S-CIA-CM14	10737495	Calibrated Temperature (°F) originating from T-type thermocouple	Surface Temp. 5
12-Bit 4-20mA Input Adapter	S-CIA-CM14	10737496	Calibrated Temperature (°F) originating from T-type thermocouple	Surface Temp. 6

Table 2: Sensor list for the "solar wall" data logger (HOBO® U30 ETH S/N 10551531)

Sensor Name	Onset Product Number	Serial Number	Channel Output	Sensor Location
Air Velocity Sensor	T-DCI-F900-L-P	10534468	Air Velocity (fpm)	Inlet Duct
12-Bit Temperature Smart Sensor	S-TMB-M0xx	10536443	Temperature (°F)	Cavity Temp. 1
12-Bit Temperature Smart Sensor	S-TMB-M0xx	10536444	Temperature (°F)	Cavity Temp. 1
12-Bit Temperature Smart Sensor	S-TMB-M0xx	10536445	Temperature (°F)	Cavity Temp. 1
12-Bit Temperature Smart Sensor	S-TMB-M0xx	10536446	Temperature (°F)	Cavity Temp. 1
12-Bit Temperature Smart Sensor	S-TMB-M0xx	10543290	Temperature (°F)	Cavity Temp. 1
12-Bit Temperature Smart Sensor	S-TMB-M0xx	10543291	Temperature (°F)	Cavity Temp. 1
Temperature/RH Smart Sensor	S-TBH-M00x	10534468	Temperature (°F) Relative Humidity (%) Dew Point (°F)	Inlet Duct

Thermography Studies

Thermography, commonly called thermal imaging, is the use of infrared cameras to analyze heat distributions. Thermography studies were performed on the Jabs Hall UTSC, in which thermal images were taken periodically throughout the day while the UTSC was running. These images help visualize shadowing effects on and airflow through the UTSC.

Infrared cameras, such as the FLIR T640 used in these thermography studies, measures the infrared radiation emitted from an object. This is a function of object surface temperature, emissivity, reflected radiation from the surroundings and the

atmospheric conditions. In order to get an accurate temperature measurement the following information must be entered into the infrared camera; atmospheric temperature, relative humidity, emissivity of the measured object, distance between the object, and the camera and reflected temperatures. Emissivity is the efficiency that an object emits thermal energy compared to that of a black body or a perfect emitter. While the emissivity of the UTSC is known, the reflected temperature must be determined before taking each individual thermal image. This is accomplished by crumpling a piece of aluminum foil, un-crumpling it and covering the measured object with it. With the emissivity on the thermal camera set to one, the measured temperature of the aluminum is the reflected temperature. This then is applied to the thermal camera's settings before taking the thermal image of the object. Figure 15 shows a thermal image used to determine the reflected temperature. There is a regular image of the UTSC overlaid with the thermal image.

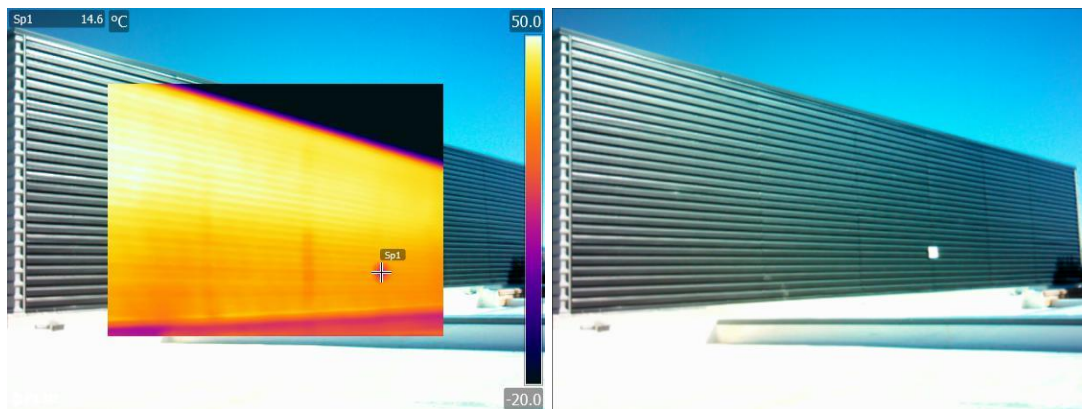


Figure 15: Determining the reflected temperature for a thermal image. Left – the thermal image overlaid with a regular photo. Right – the regular photo, showing the relative sized of aluminum foil used to determine the reflected temperature.

It can also be seen that the thermal images are taken off axis, meaning that the infrared camera isn't perpendicular to the UTSC. This isn't ideal, however it was required due to limited roof space. As previously stated, one of the inputs to the infrared camera is object distance. As the thermal images were taken off axis the true object distance will vary but only one value, the average, was entered. Error due to this will be examined in the section titled "Distance Error of Infrared Camera."

Four thermography studies were performed and are documented in the appendices of this document. Table 3 outlines the thermography study dates and appendix location. Plots of temperature, wind speed, wind direction and solar radiation over the test duration are included in the beginning of each appendix to provide insight into the weather the UTSC was experiencing during the test. Thermal images and traditional photos are shown side-by-side giving further indication of the weather during the test.

Table 3: Thermography study dates and appendix location

Thermography Study Date	Documenting Appendix
October 5 th , 2015	Appendix A
October 23 rd , 2015	Appendix B
November 4 th , 2015	Appendix C

ENERGY MODEL DEVELOPMENT

The main component of the energy model under examination is the EnergyPlus UTSC component, however, the rest of Jabs Hall must be included in the model in order to accurately represent the buildings operation. The entire mechanical system of the building must be modeled in a fashion that represents how Jabs Hall operates and include the operation controls for utilization of the UTSC. The UTSC in the energy model must operate as it would in a field study given the same weather and operation profile; when the air exiting the UTSC is above the required temperature by the HVAC system, the UTSC is bypassed and air is brought in from a different intake louver. A holistic modeling approach will be taken to accomplish this and is outlined below.

Building Geometry

The OpenStudio plugin for SketchUp was used to develop the energy model building geometry. The benefit of doing it in this manner is that the floor plan can be drawn and then projected into spaces. Once these building spaces are developed sub-surfaces – such as windows and doors – can be drawn directly on the model surfaces. This method is preferable compared to the traditional method – seen in other energy modeling software packages – of entering the coordinates and dimensions for every surface and sub-surface of a building. Figure 16 shows the energy model from the southeast. Figure 17 and Figure 18 show various views of Jabs Hall, comparing an actual photograph to the created energy model.

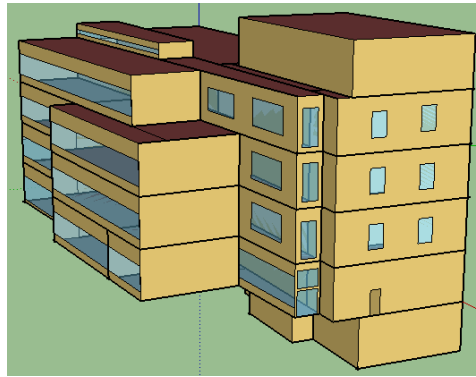


Figure 16: View of the Jabs Hall energy model from the southeast.

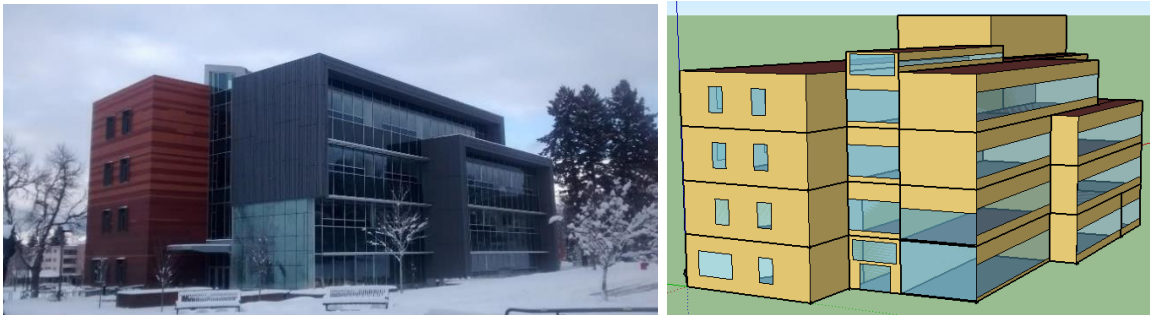


Figure 17: View of Jabs Hall from the southwest. Left - photograph. Right - energy model.



Figure 18: View of Jabs Hall from the north. Left - photograph. Right - energy model.

Shading Object

The trees to the southeast of the UTSC were represented by a shading object. As seen in Figure 19, this shading object was opaque and will cast shadows on the building and UTSC.

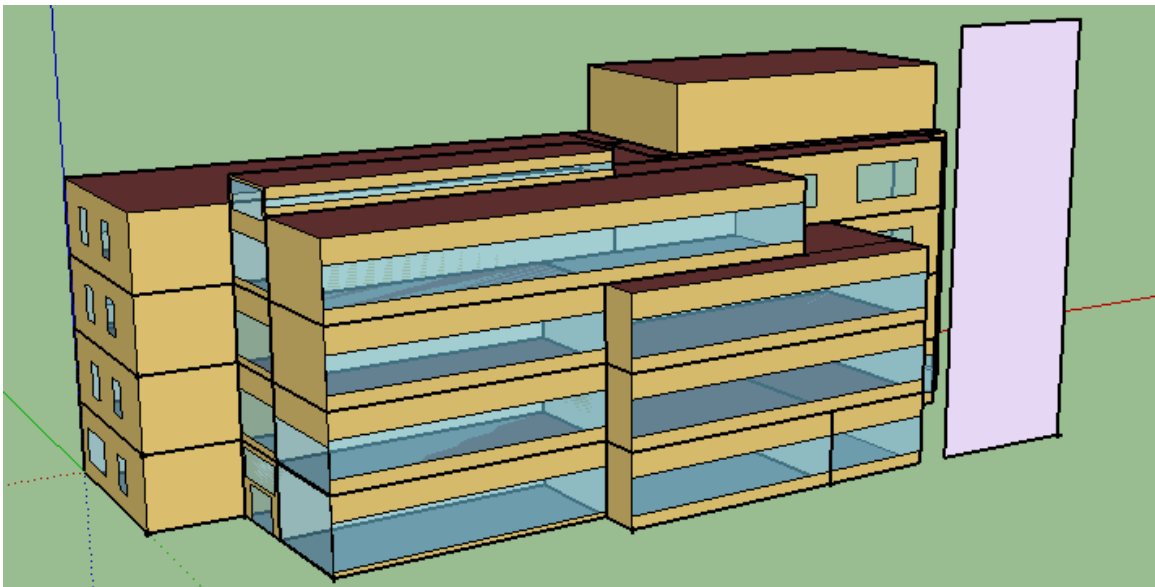


Figure 19: Shading object that represents the trees southeast of the UTSC

Space Types

As with any type of modeling, it is important to document assumptions and simplifications made about the modeled object. In energy modeling for buildings, these include both the physical and operational characteristics of the building. When creating an energy model it is advantageous to break up the building into different space types, or spaces that share similar programmatic functions and loading characteristics. One could define a different space type specific to each room in a building, however, at some point there is a diminishing return on the number of space types when compared to model accuracy and computation time. Smart selection of space types should be based on distinguishing, unique characteristics such as occupancy, lighting, plug loads, usage schedules, thermostat set points, ventilation rates and infiltration definitions. Occupancy is characterized by the schedule of occupation, occupant density and occupant activity

levels. Standard occupancy density of various spaces are listed in *ANSI/ASHRAE/IES Standard 62.1: Ventilation for Acceptable Indoor Air Quality* (ASHRAE Standard 62.1). Lighting is defined by the lighting power density (LPD). Energy standards such as ASHRAE Standard 90.1 define the maximum lighting power allowed in a space based on the function of the space. Plug loads are directly related to function of the space. ASHRAE has published values of standard equipment or plug loads in the *ASHRAE Handbook – Fundamentals*. Ventilation requirements, defined in ASHRAE Standard 62.1, relate to occupancy density, function a space serves and the size. Infiltration describes the air leakage in or out of a building. Building pressure, wind pressure and construction quality are all factors in infiltration rates. Infiltration is expressed by air change per hour (ACH) values. The published values in the various standards mentioned above are used as a starting point to define the building loads in an energy model.

For modeling Jabs Hall, seven space types were selected. These space types include classroom, office, corridor, mechanical/electrical room (MechElec), restroom, lobby and café. These space types are shown in Figure 20 both as the entire building and by the floorplan.

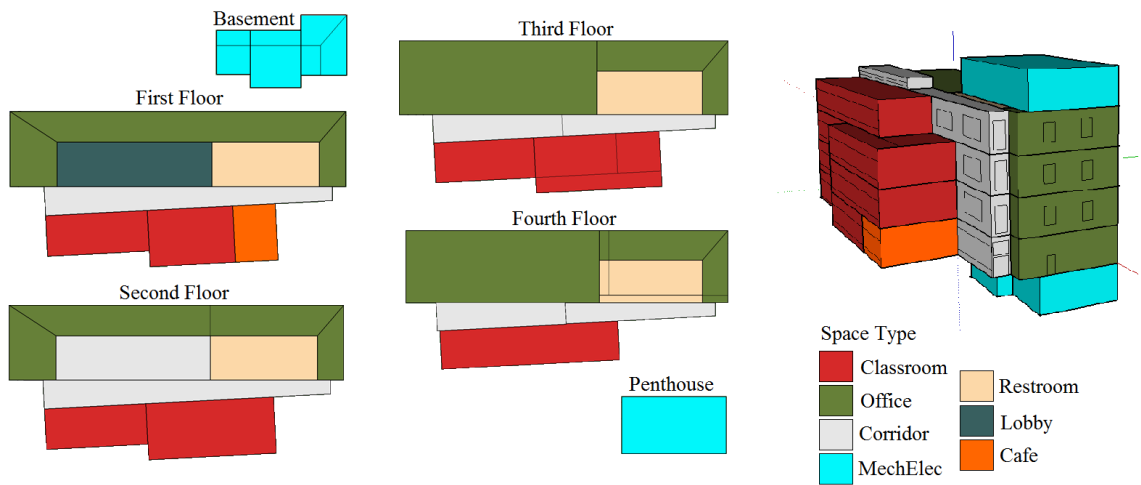


Figure 20: Jobs Hall modeled space types, shown in the entire modeled building and by the floorplan.

Schedule Sets

Each of these space types have maximum values defined for occupancy, lighting, plug loads and ventilation rates. These values are typically pulled from the standards as discussed above, unless supplemental testing is performed. These maximum loads are not assumed to occur one-hundred percent of the time. This is where schedules are applied. Schedules dictate what percentage of the full load – occupancy density, lighting or plug load – are experienced as a function of time. Schedules can vary throughout the day, different days of the week, or different weeks in the year. For instance, the occupant density schedule for classrooms will vary based on if it is a weekday, weekend, or a holiday. Once appropriate schedules are made for the entire building and space loads, these schedules can be grouped together to create a schedule set. There is a schedule set created for each space type.

Construction Sets

The construction, or what the building is made of, is detailed in a similar fashion. Individual materials are created and their parameters such as thickness, roughness, conductivity, density, specific heat, thermal absorptance and solar absorptance are defined. Then these materials are layered to create constructions. These constructions can be that of a door, exterior wall, or roof for example. These construction are combined into a construction set. There can be multiple construction sets for a building, however a single construction set was used for Jabs Hall.

HVAC System and Thermal Zones

Jabs Hall HVAC System Overview

Heating, ventilation and air-conditioning (HVAC) systems condition spaces within buildings. Air-conditioning is a comprehensive term including the processes of heating, cooling, humidifying, dehumidifying, ventilating, cleaning and/or moving air for a building. The HVAC system in Jabs Hall consists of two air handling units (AHU) that serve different spaces within the building with slightly different strategies.

AHU-A serves the classrooms and the core of the building. AHU-A supplies constant 12.8°C (55°F) air to terminal variable air volume (VAV) boxes with reheat capabilities. When a room served by AHU-A requires cooling, the 12.8°C (55°F) air is used directly. When heating is required, the 12.8°C (55°F) air is supplied to the VAV box and reheated at the point of use to the required temperature to reach the thermostat set point. The volume of air supplied to each VAV box varies based on what is required to

reach the thermostat set point and to satisfy acceptable indoor air quality. This control strategy is beneficial for buildings that have heating and cooling loads simultaneously, or that have spaces with drastic spikes in thermal loads such as classrooms or rooms with heavy amounts of glazing, or windows. Supplemental heat is supplied via fin tube heaters along the perimeter.

AHU-B serves the offices within Jabs Hall. As the offices experience a fairly steady occupant load and are on the north side of the building, the air demands are expected to be similar. AHU-B supplies air to terminal VAV boxes without reheat in the offices to satisfy ventilation requirements. Supplemental heat is supplied via fin tube heaters along the perimeter.

A heat pump plant, located in the adjacent building Leon Johnson, supplies the building hot and chilled water, at 60°C (140°F) and 7°C (45°F) respectively. These hydronic loops supply the appropriate water to the heating and cooling coils in the AHUs, to the reheat coils in the VAV boxes with reheat capability, and to the fin tube heaters.

Energy Model Thermal Zones

Understanding the operational characteristics of the HVAC system in Jabs Hall at a high level is required to assign thermal zones in the energy model. At a minimum, there needs to be a thermal zone assigned to the spaces served by each AHU. In a more detailed energy model for design purposes many thermal zones would be assigned based on the control strategy and loads expected. However for the purposes of this research a coarser approach was taken – closer to what is done for general equipment sizing – in which fewer thermal zones are selected to represent different HVAC control strategies or

drastically different loading patterns experienced. For the Jabs Hall energy model, three thermal zones were identified and shown in Figure 21. The north thermal zone is served by AHU-B. The south and core thermal zones are served by AHU-A. It was decided to create two thermal zones for AHU-A primarily due to the loading characteristics. The spaces in the south thermal zone will experience fluctuations in thermal loading due to the large percentage of glazing on the southern façade. These spaces are also classrooms and will see spikes in thermal loading due to the occupancy characteristics. The spaces in the core thermal zone should experience more consistent thermal loading.

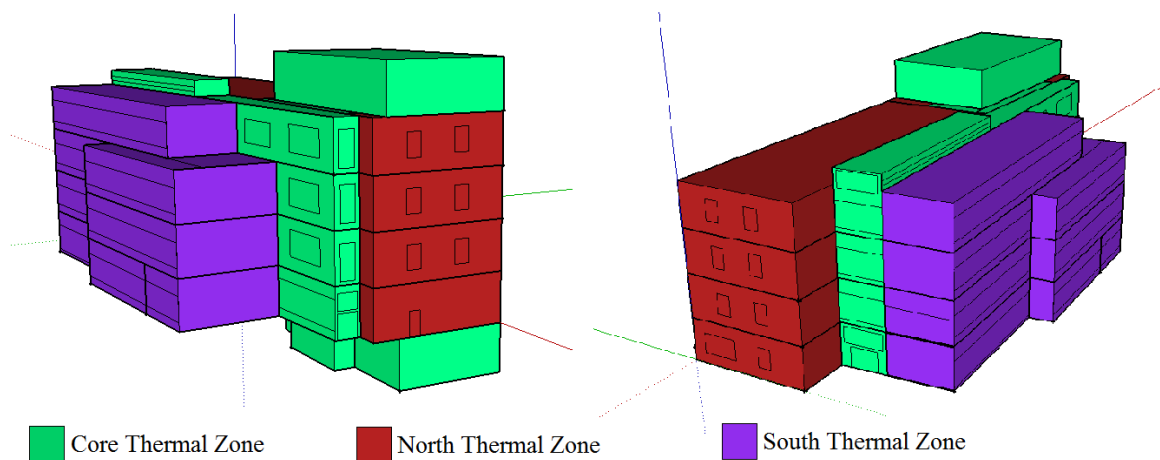


Figure 21: Thermal zones for the Jabs Hall energy model.

HVAC Schedule

The HVAC system in Jabs Hall has two modes: occupied and unoccupied mode. Jabs Hall is in occupied mode 06:30 to 22:00 Monday through Thursday and 06:30 to 19:00 on Fridays. The building is in unoccupied mode on the evenings, weekends and holidays. The three weeks before and during finals week Jabs Hall will be in occupied mode on the weekends from 09:30 to 17:30. Table 4 summarizes the temperature settings

for occupied mode based on space type and season. When Jabs Hall is in unoccupied mode in the winter, the temperature set point is 18°C (65°F). The building is not cooled in the summer in unoccupied mode.

Table 4: Occupied mode temperature settings for Jabs Hall based on space type and season

Space Type	Offices		Classrooms & Public Spaces	
Season	Summer	Winter	Summer	Winter
Range	22-27°C (72-80°F)	20-27°C (68-80°F)	22-24°C (72-76°F)	20-23°C (68-74°F)
Set Point	23°C (74°F)	20°C (68°F)	24°C (75°F)	20°C (68°F)

Energy Model HVAC Schematics

Based on the information discussed about the HVAC system in Jabs Hall and how it is expected to operate, simplified schematics were created to express the energy model HVAC system. Figure 22 is a schematic of the air loops created in the Jabs Hall energy model, including the air loops for both AHU-A and AHU-B. Figure 23 is a schematic of the hydronic loops for the energy model: hot and chilled water. All but one component in these schematics can be created in OpenStudio; the UTSC component must be added to the EnergyPlus text code by hand and is discussed in the section titled Energy Plus and the UTSC.

Simplified Air Loops: AHU-A & AHU-B

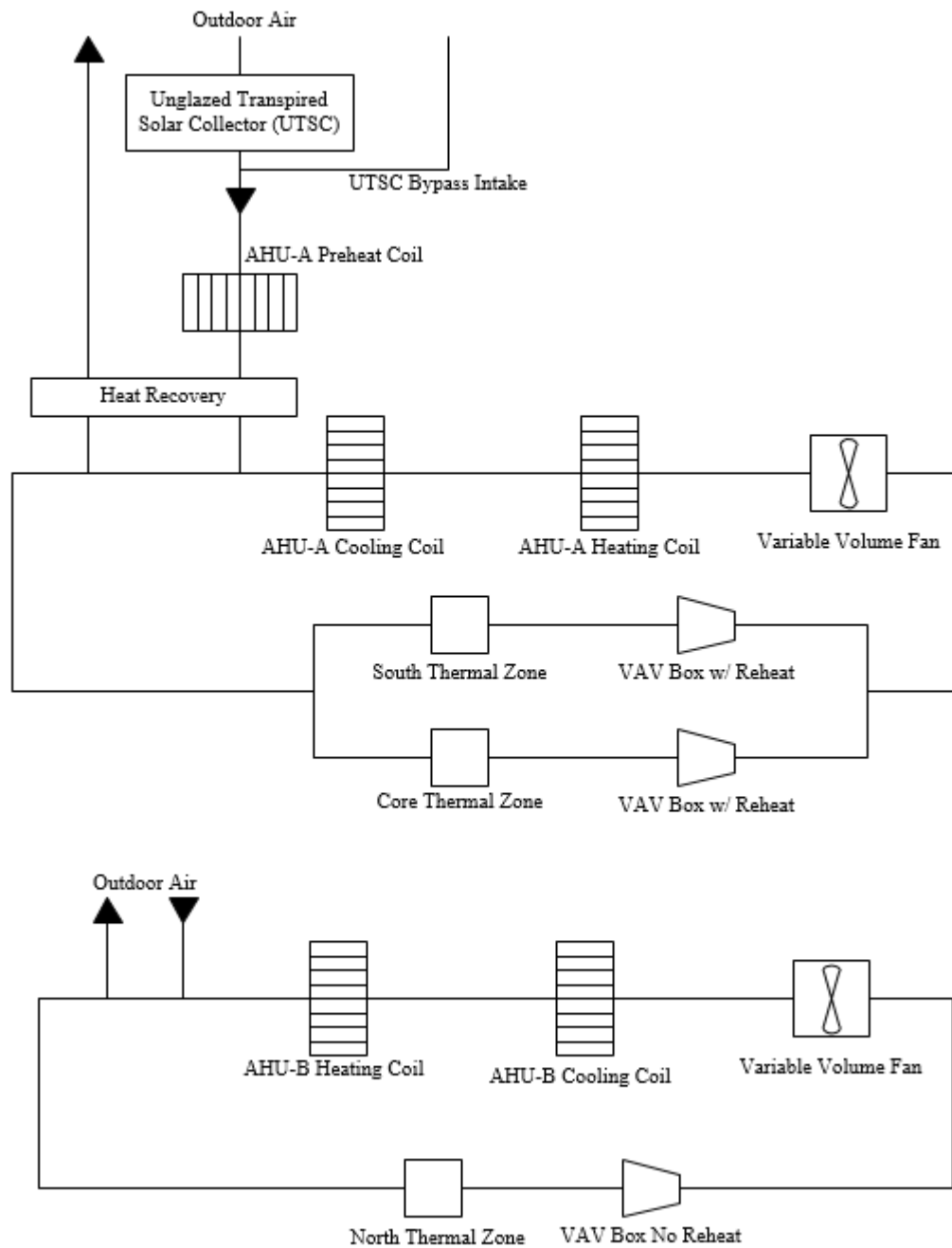


Figure 22: Schematic of simplified air loops used for the Jabs Hall energy model.

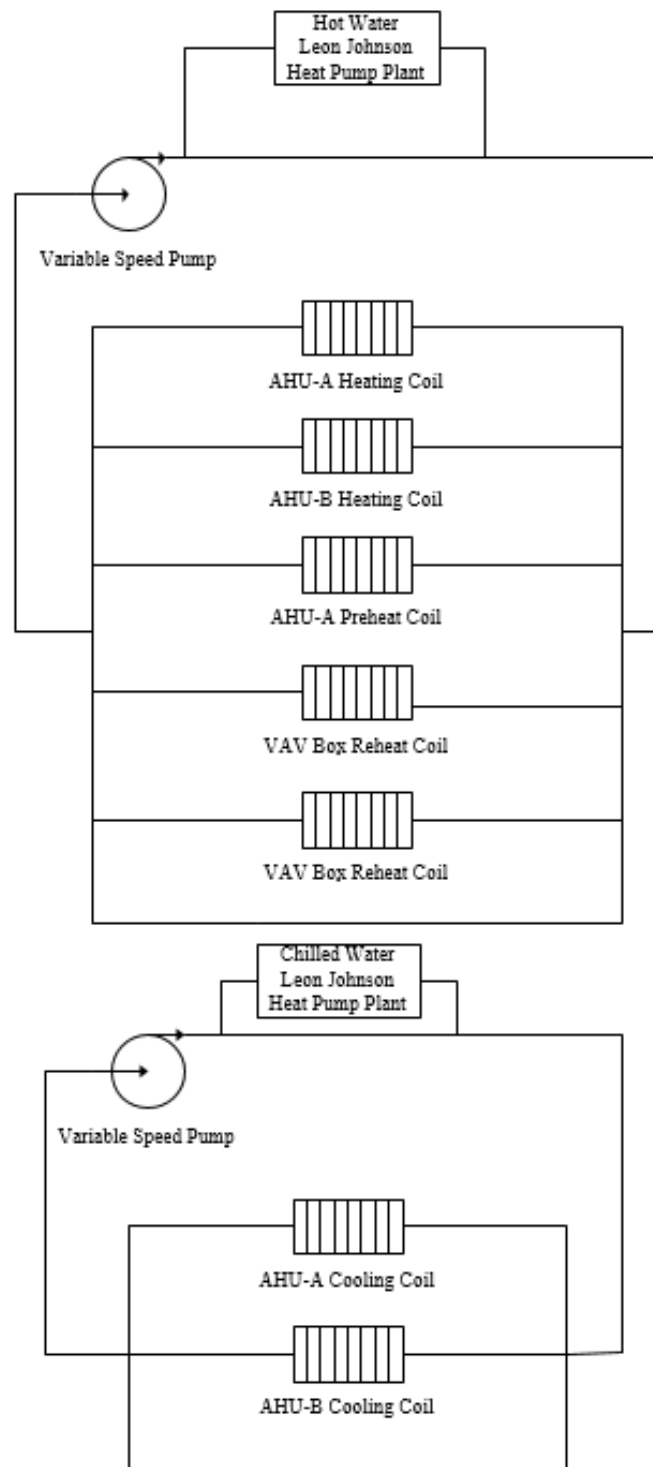
Simplified Hydronic Systems: Hot and Chilled Water

Figure 23: Schematic of simplified hydronic loops used for the Jabs Hall energy model.

Using OpenStudio

When creating the Jabs Hall energy model, OpenStudio and the OpenStudio plugin for SketchUp were primarily used for creating the EnergyPlus Input Data File (IDF). Here is a general review of the steps taken in OpenStudio.

- Draw spaces and building geometry in SketchUp with the OpenStudio plugin.
- Save the file as an OpenStudio model (OSM). Work with the model in the OpenStudio program for the remainder of the steps.
- Apply the appropriate weather and design day files.
- Create schedules and schedule sets.
- Create constructions and construction sets.
- Define building loads including occupancy, lighting, plug loads, ventilation requirements and infiltration rates.
- Create space types; assign construction sets, schedule sets and loads to the space types.
- Apply the space types to the physical spaces drawn previously in SketchUp.
- Create the thermal zones and apply them to the appropriate spaces.
- Create the HVAC system that ties into the thermal zones.

At this point the main component missing to represent the Jabs Hall in the energy model is the UTSC. As previously stated, this component is not yet incorporated into OpenStudio, so it has to be added to the EnergyPlus text code by hand. Export the OSM to an EnergyPlus IDF.

Energy Plus and the UTSC

There are three components that are significantly altered or added to the text code or IDF for the addition of a UTSC. First the building surface or wall on which the UTSC is located needs to reflect the altered boundary condition by changing it to “OtherSideConditionsModel.” Give this boundary condition a reference name in the boundary condition object field. Second, a surface property for this “OtherSideConditionsModel” must be created. The same reference name was used and the type of modeling was noted as “GapConvectionRadiation” to reflect the heat transfer mechanisms experienced by the UTSC. Third, the UTSC object was created. The boundary condition previously defined was entered along with the physical and operational characteristics of UTSC as dictated by the UTSC object format. The UTSC output variables of interest can be noted to the IDF to have EnergyPlus report them at various frequencies such as over the time step, hourly or monthly. Some of these variables include the UTSC effectiveness, air temperature leaving the collector, face suction velocity, plenum air temperature, sensible heating rate, sensible heat energy, incident solar radiation, system efficiency and surface efficiency. Once these three steps are complete the IDF is complete and the IDF is ready to be executed by EnergyPlus.

Weather Files and Data

One of the largest issues with energy modeling is appropriately accounting for weather. EnergyPlus uses a typical meteorological year (TMY) file. A TMY file has a year’s worth of weather data. Every hour in this file has averages of temperature, wind

speed, solar irradiation, et cetera for that hour on an annual basis, which effectively eliminates the extremes in weather experience at that particular location.

In the case of evaluating the UTSC for this research, some of the operating conditions of interest are the extreme cases of weather. A weather file was created using data collected at the test site for two reasons. First, to evaluate the UTSC in extreme weather conditions. Second, so the model can be directly compared to experimental data collected.

Big Ladder Software LLC based out of Denver, Colorado has created an open-source program for creating and editing weather files called Elements. [19] Elements has many inputs that a user can use to define a weather file; Some of the commonly used inputs are latitude, longitude, time zone, elevation, dry bulb temperature, wet bulb temperature, relative humidity, dew point temperature, atmospheric temperature, global solar irradiance, normal solar irradiance, diffuse solar irradiance, wind speed and wind direction. However, not every input needs to be entered by the user. For instance, if the user defines the atmospheric temperature, dry bulb temperature and relative humidity the program will auto-calculate the wet bulb and dew point temperature based off psychrometric relationships. Similarly, two of the three solar irradiance components need to be defined by the user and the program will auto-calculate the third component using the relationship defined in Equation (24). [20]

$$I_{global} = I_{normal} \cdot \cos(Z) + I_{diffuse} \quad (24)$$

In this relationship I_{global} is the global or total solar irradiation on a horizontal surface, $I_{diffuse}$ is the diffuse or scattered irradiation on a horizontal surface, Z is the zenith angle, and I_{normal} is the normal or direct irradiation. The normal component is from the direction

of the sun and is dependent on the zenith angle. The zenith angle, as shown in Figure 24, is the angle between the sun and the vertical and varies based on location and time of year.

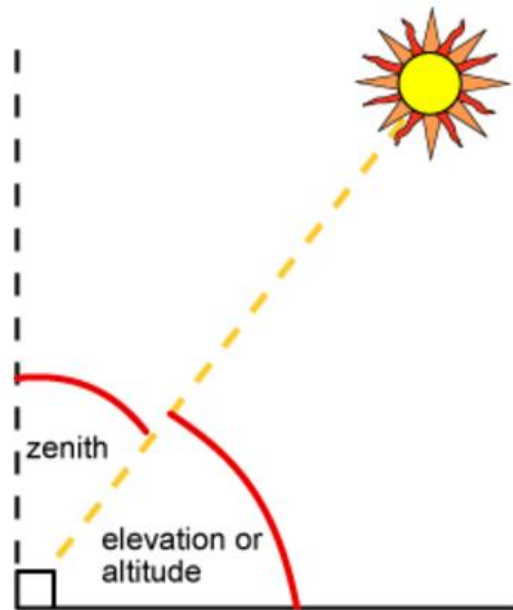


Figure 24: Zenith Angle [21]

The generated custom weather file used collected weather data from the Jabs Hall weather station for October 17th, 2015 through November 6th, 2015 and the standard Bozeman Gallatin Field weather file for all other days. The collected weather data included dry bulb temperature, relative humidity, wind speed, wind direction and global solar irradiance. To completely define the weather, atmospheric pressure was used from the Cobleigh Hall weather station [12] and the diffuse solar irradiance was estimated.

Estimating Diffuse Solar Irradiation

On a clear, sunny day about 10% of global irradiance is diffuse. [22] To estimate the diffuse irradiance a curve fit must be established for the global irradiation for a

typical sunny day for the time of year. Once an appropriate fit is applied to the global irradiation, it is multiplied by 0.1 to create a diffuse trend. Figure 25 displays four global solar irradiance trends. October 21st represents the global solar irradiance on a sunny day, October 17th represents a mostly sunny day, October 19th a partly cloudy day and October 20th a mostly cloudy day. On October 17th, 19th, and 20th it can be observed that the amount of cloud cover varies throughout the day.

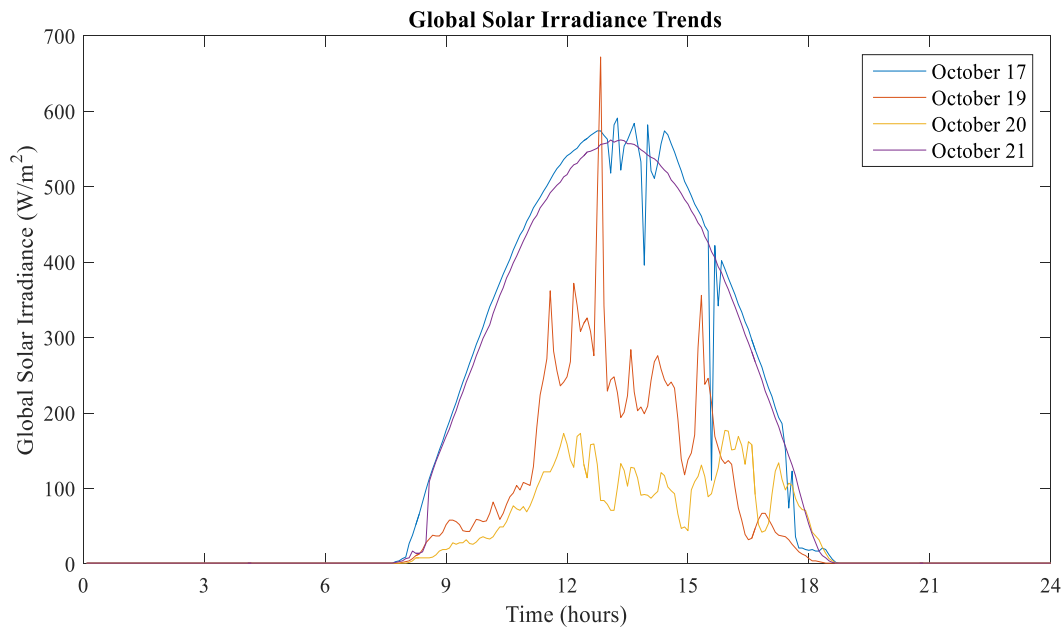


Figure 25: Global solar irradiance trends.

At a first glance of global irradiance trends, Figure 26, a Gaussian fit appears to be appropriate for this application. It can be seen that on partly cloudy days such as October 19th and 20th, the global irradiance lines approach and sometimes reach the diffuse fit, representing a fully cloudy moment, but do not drop below this line. This is a relatively appropriate representation of the diffuse irradiance for this time of year. However, it overestimates the diffuse irradiation at sunrise and sunset which results in cloudy

modeled sunrises and sunsets. This isn't ideal when analyzing the USTC as mornings are an important operation time. Due to this a second-order polynomial fit was analyzed next.

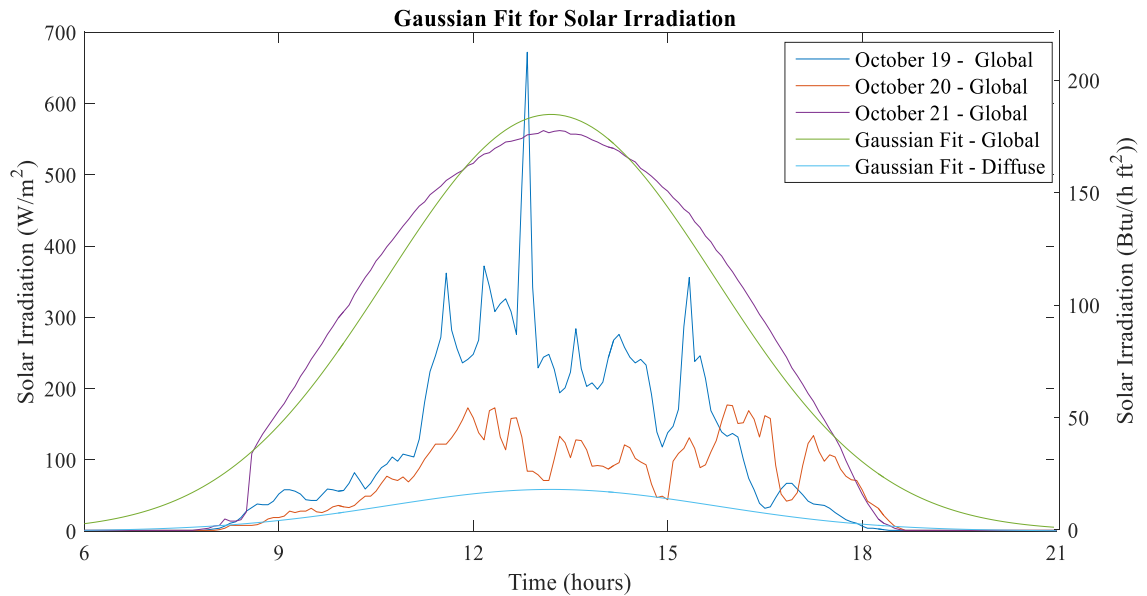


Figure 26: Gaussian fit for diffuse solar irradiation

The second-order polynomial fit for diffuse irradiation, Figure 27, is more appropriate.

This fit better represents the characteristics at sunrise and sunset and is an overall improved fit. This fit was used to estimate the diffuse solar irradiation for October 17th, 2015 through November 6th, 2015 in the modified weather file.

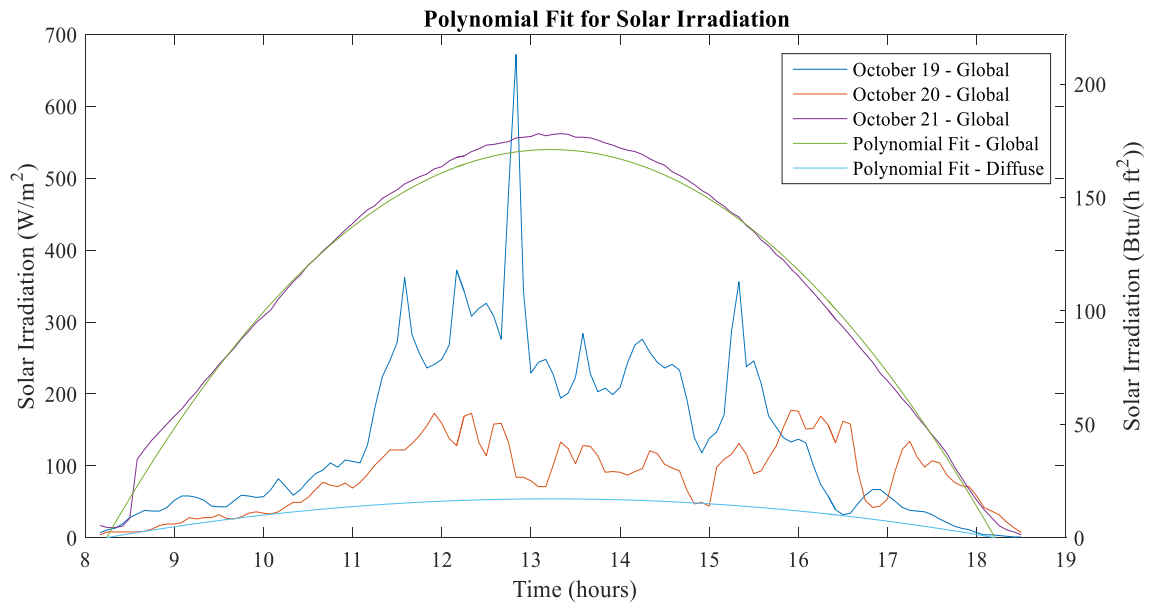


Figure 27: Second-order polynomial fit for diffuse irradiation

RESULTS

Raw Data

Appendix D has plots of the raw data collected at Jabs Hall, excluding surface and cavity temperatures, for September 9th, 2015 through November 17th, 2015. A few days within this range were omitted from this appendix due to data acquisition issues. Figure 28 is an example of the plots found in Appendix E. Each day has 5 plots; the first is the outdoor air and AHU-A inlet air temperatures, the second is wind and gust speeds, the third is the wind direction in degrees where zero is north, the fourth is the global solar irradiance, and the fifth is velocity in the AHU-A inlet duct. The wind anemometer monitors the wind velocity over a five minute interval and records two values – wind and gust speeds. The wind speed is the average velocity over the 5 minute interval and the gust speed is the maximum velocity experienced during that same period of time. The AHU-A velocity plot is used to quickly recognize when the UTSC is being utilized. The maximum designed flow rate through the UTSC is approximately 8 m/s (1500 fpm). The difference in temperatures between the outdoor air and AHU-A when the UTSC is being utilized is directly related to free heat gained from the UTSC. It can be observed from these plots that the weather and therefore the heat transfer mechanism affecting the UTSC are highly transient in nature.

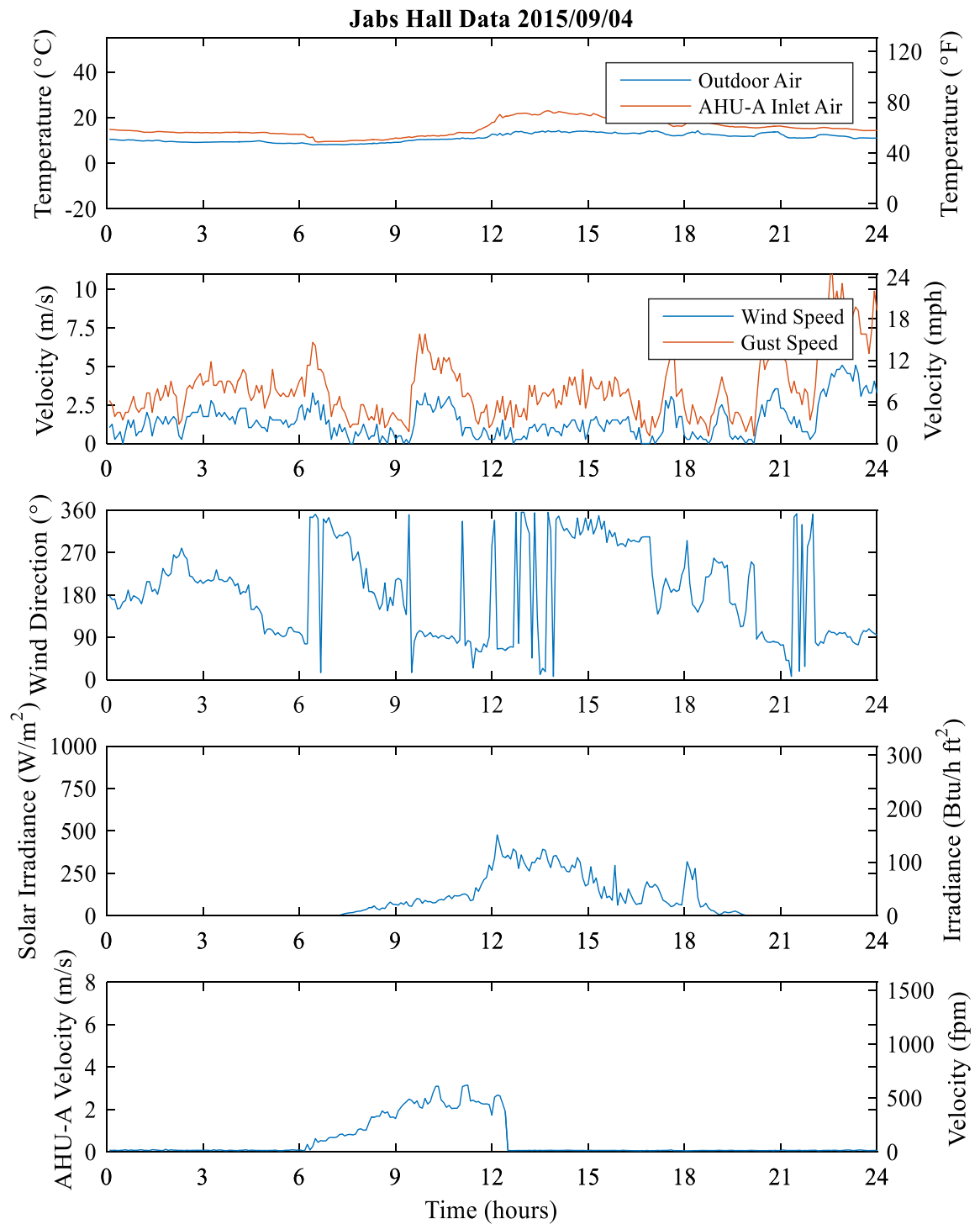


Figure 28: Raw data collected on 2015/09/04

Filtering Data

Both the surface and cavity temperatures had some irregularity and noise relative to each other due to the transient nature of the weather conditions being experienced by the UTSC. However, the noisy quality was amplified for the surface temperatures. The surface temperatures were measured by thermocouples, which are a relatively noisy compared to other temperature measurement devices such as thermistors and resistance-temperature detectors (RTDs), and were mechanically fastened to the UTSC surface. The thermocouple signal was also required to be converted to a 4-20 mA signal before it could be read by the data acquisition box. All of which contributes to why the surface temperatures were noisier than all other collected data. Figure 29 is a plot of the raw surface temperature data and Figure 30 is plot of the raw cavity temperature data both on November 4th.

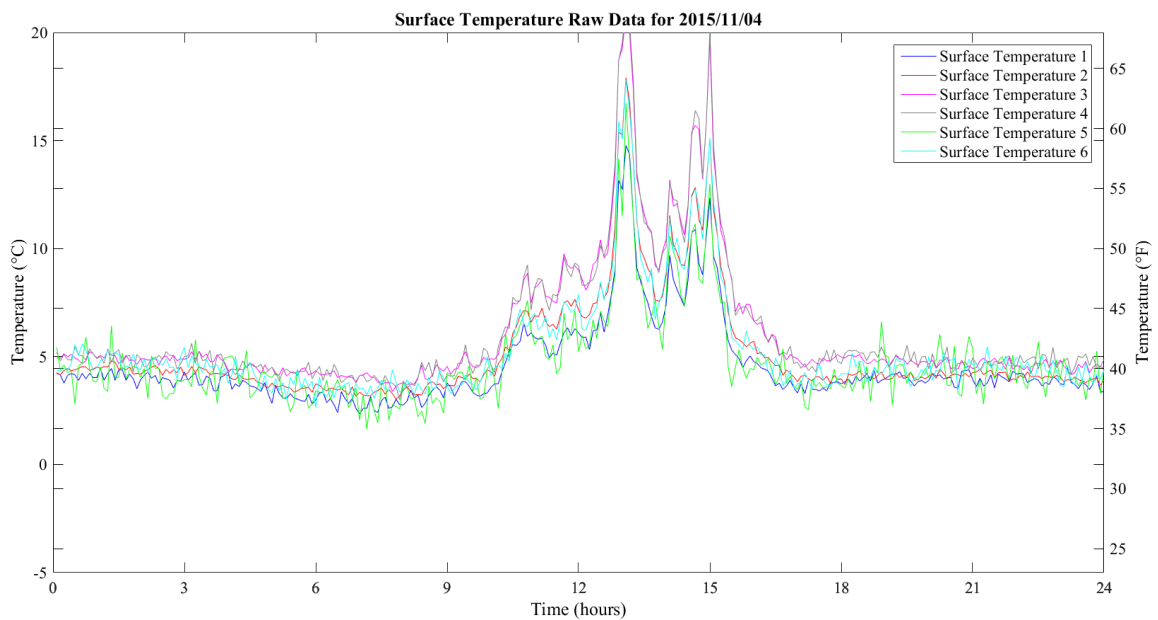


Figure 29: Raw surface temperature data for 2015/11/04

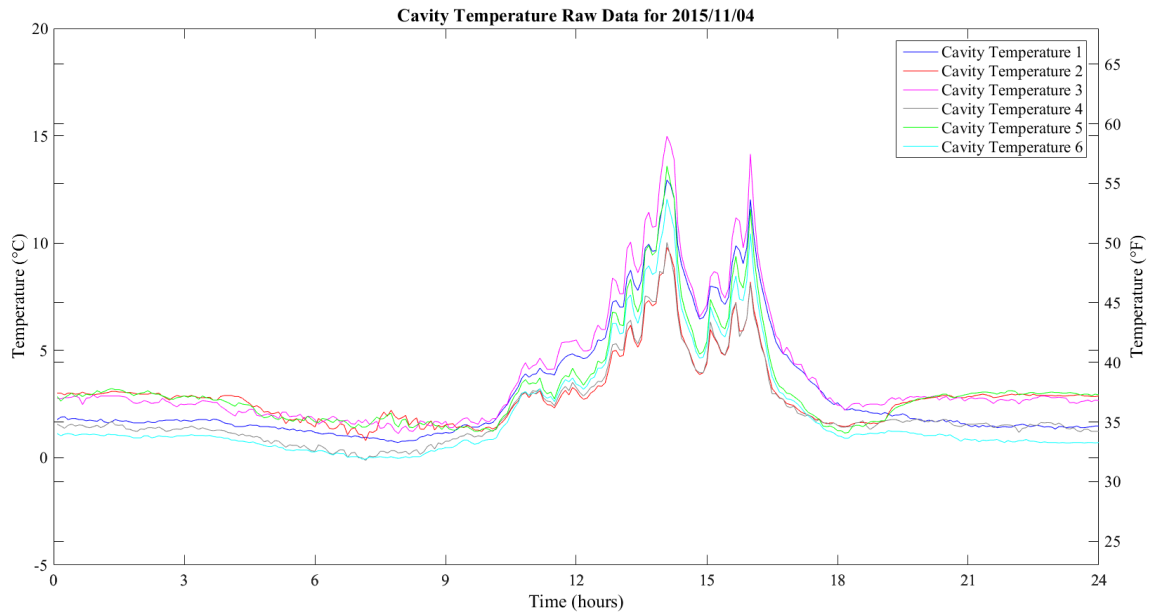


Figure 30: Raw cavity temperature data for 2015/11/04

These plots are a small sample of the total data collection but are representative of data quality for surface and cavity temperatures. A filter was applied to the surface and cavity temperature data sets before performing calculations. Ultimately a first-order Butterworth low-pass filter was selected. Often the Butterworth filter is described as having a flat response. A Fourier transform of a sample data set was used to identify a range of appropriate cutoff frequencies. These potential cutoff frequencies were utilized in the filtering and applied to a surface temperature data set and then compared to surface temperature data collected from a thermography study. The selected normalized cutoff frequency was 0.33 cycles/sec, as it didn't dramatically decrease the temperature values when compared to the thermography study data. This filter was used to smooth the raw data collected for surface and cavity temperature before performing calculations. Figure 31 and Figure 32 are plots of the filtered temperature data for the surface and cavity, respectively, on November 4th. The surface temperature sensors are T-type thermocouple

that are mechanically fastened to the surface of the UTSC. Filtering the surface temperature data is important to eliminate the noise of the sensors relative to each other, however the data set will still be very transient in nature due to the irregular nature of solar irradiance through the day. The same filter was applied to both surface and cavity temperature data for consistency.

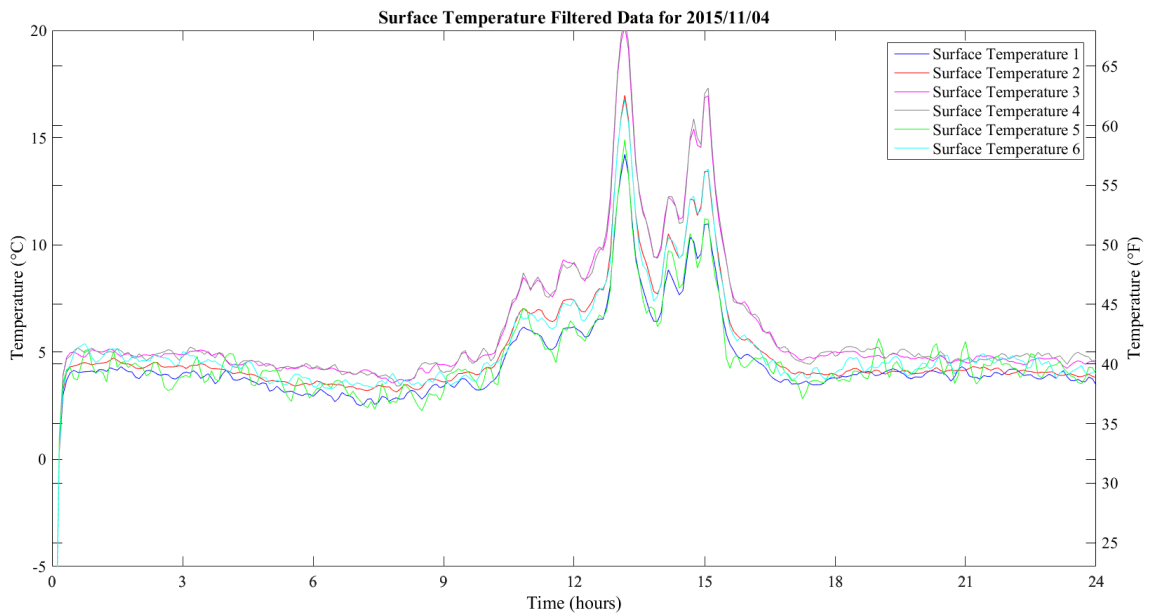


Figure 31: Filtered surface temperature data for 2015/11/04

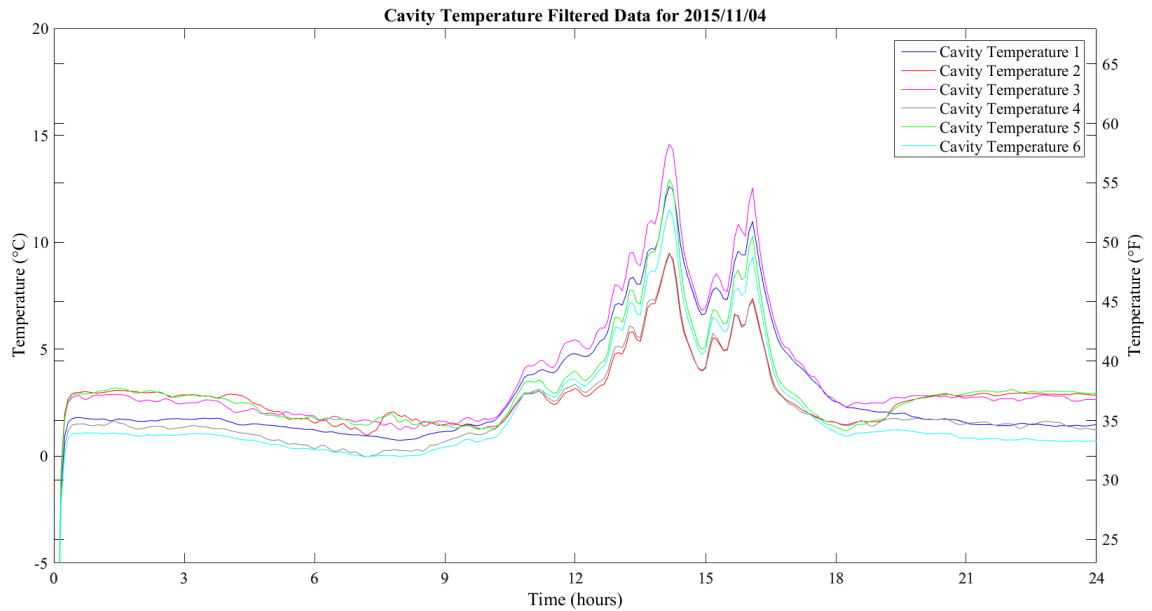


Figure 32: Filtered cavity temperature data for 2015/11/04

It can be observed that the selected filter creates inaccuracies in the data for the first 30 minutes. This is acceptable because the UTSC will not be operated during these hours and therefore will not be used in calculations. Figure 33 and Figure 34 are respectively the raw and filtered surface temperature data for October 23rd.

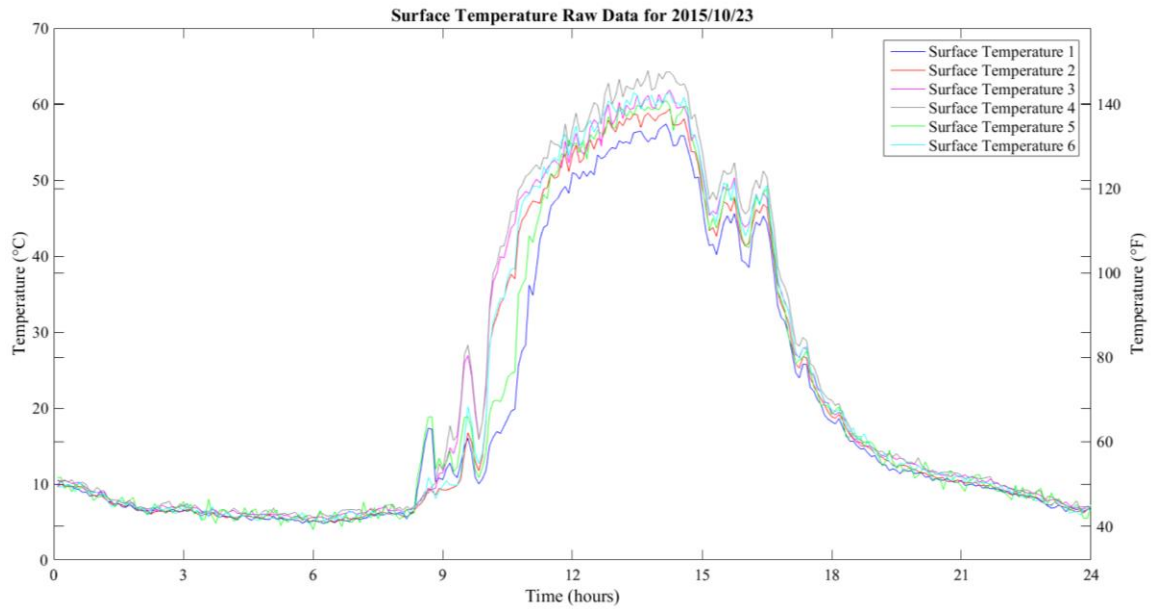


Figure 33: Raw surface temperature data for 2015/10/23

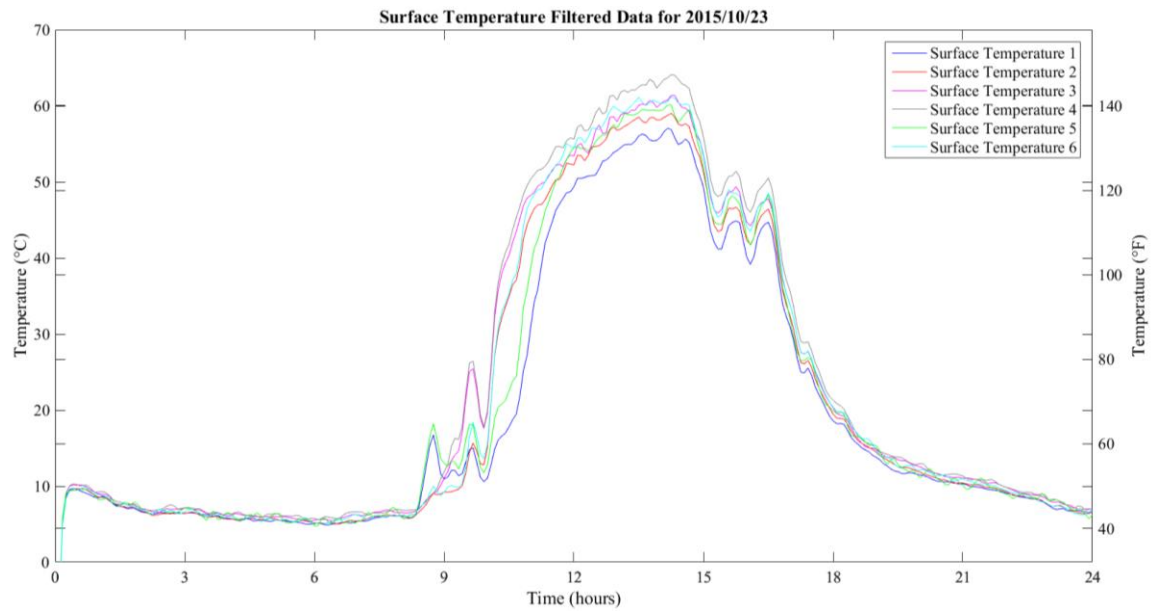


Figure 34: Filtered surface temperature data for 2015/10/23

Approximating Temperature Profiles

Equation (7) was discretized using two different rectangular meshes, coarse and fine. The temperatures are linearly interpolated and extrapolated along the entire profile

for each mesh. The fine mesh is a 2.54 cm by 2.54 cm (1" x 1") grid. The coarse mesh is a 2 m by 6.7 m (6'6" x 22'1/3") grid. Figure 35 through Figure 38 show contour plots of the resultant surface and cavity temperature profiles using the fine mesh at four times on October 23rd, 2015. For comparison, Figure 38 also has a contour plot of the surface temperature profile using the coarse mesh. Figure 39 has infrared images of the UTSC at these same times on October 23rd, 2015 to be compared directly to the surface contour plots. These infrared images not only have a color bar to give indication of surface temperatures of the UTSC, but there are also discrete points shown along the surface marked by crosshairs that correspond to specific temperature values in the upper left corner of the image.

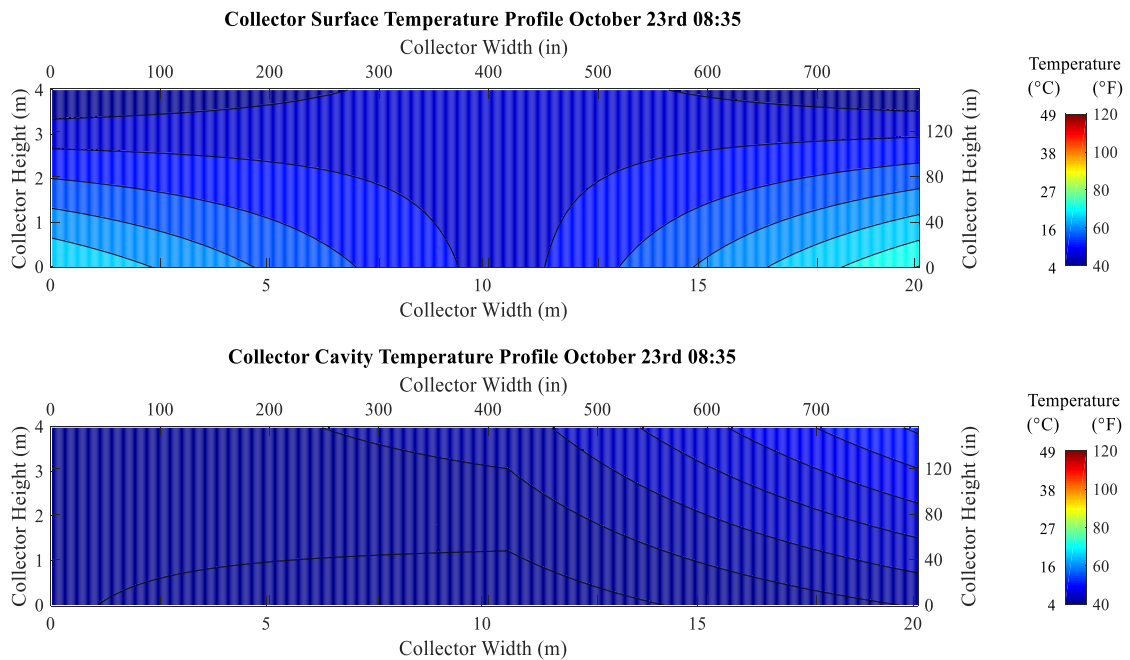


Figure 35: Collector surface and cavity temperature profiles October 23rd 08:35

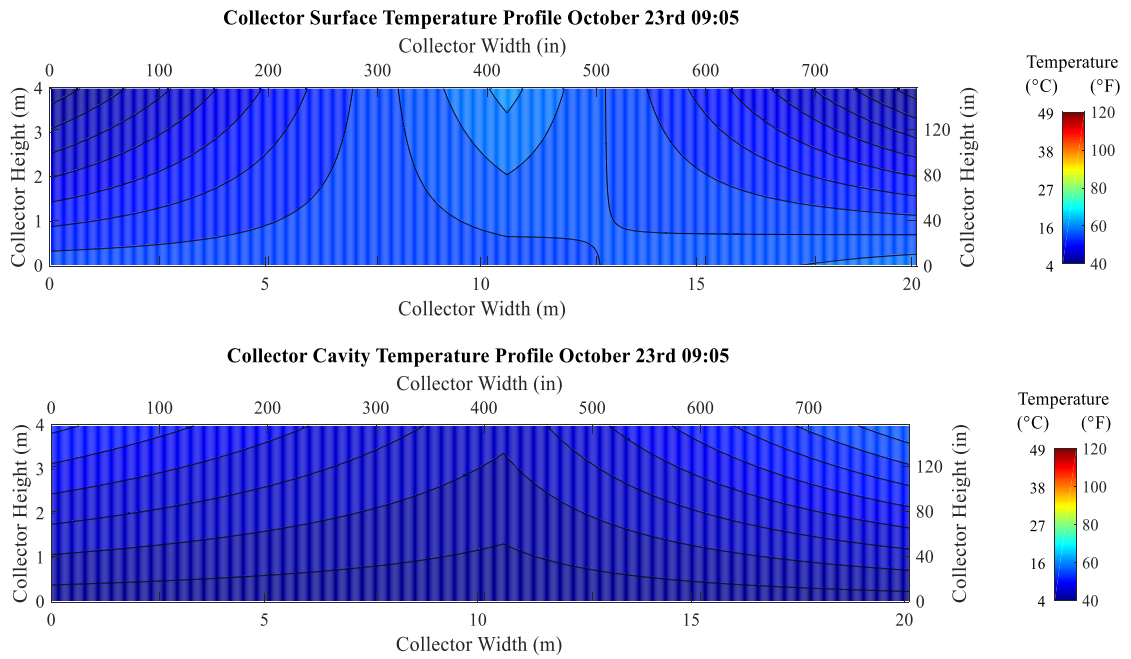


Figure 36: Collector surface and cavity temperature profiles October 23rd 09:05

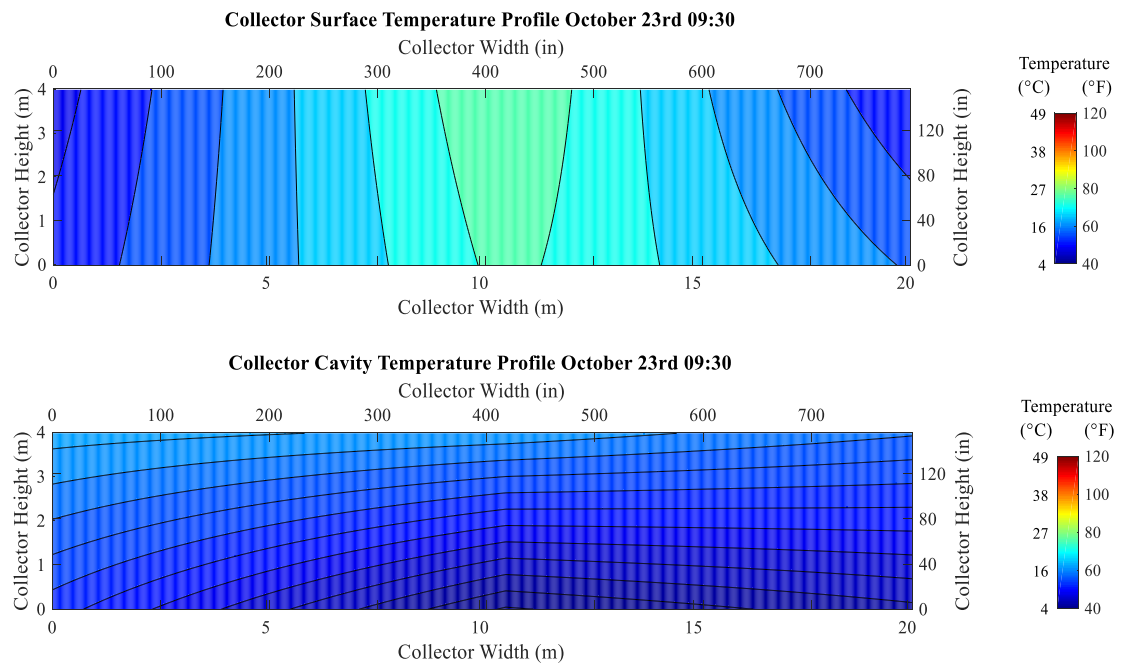


Figure 37: Collector surface and cavity temperature profiles October 23rd 09:30

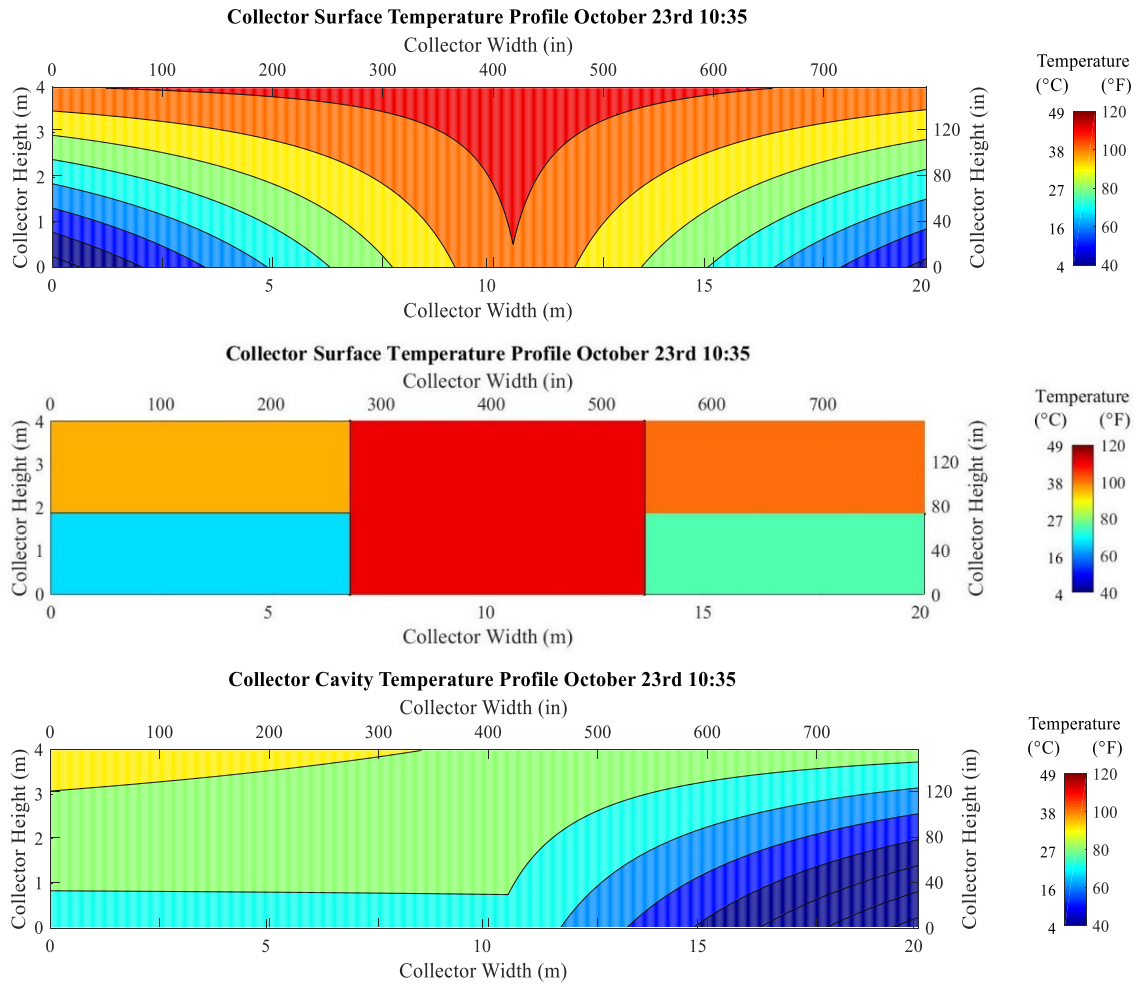


Figure 38: Collector surface (fine and coarse mesh) and cavity temperature profiles October 23rd 08:35

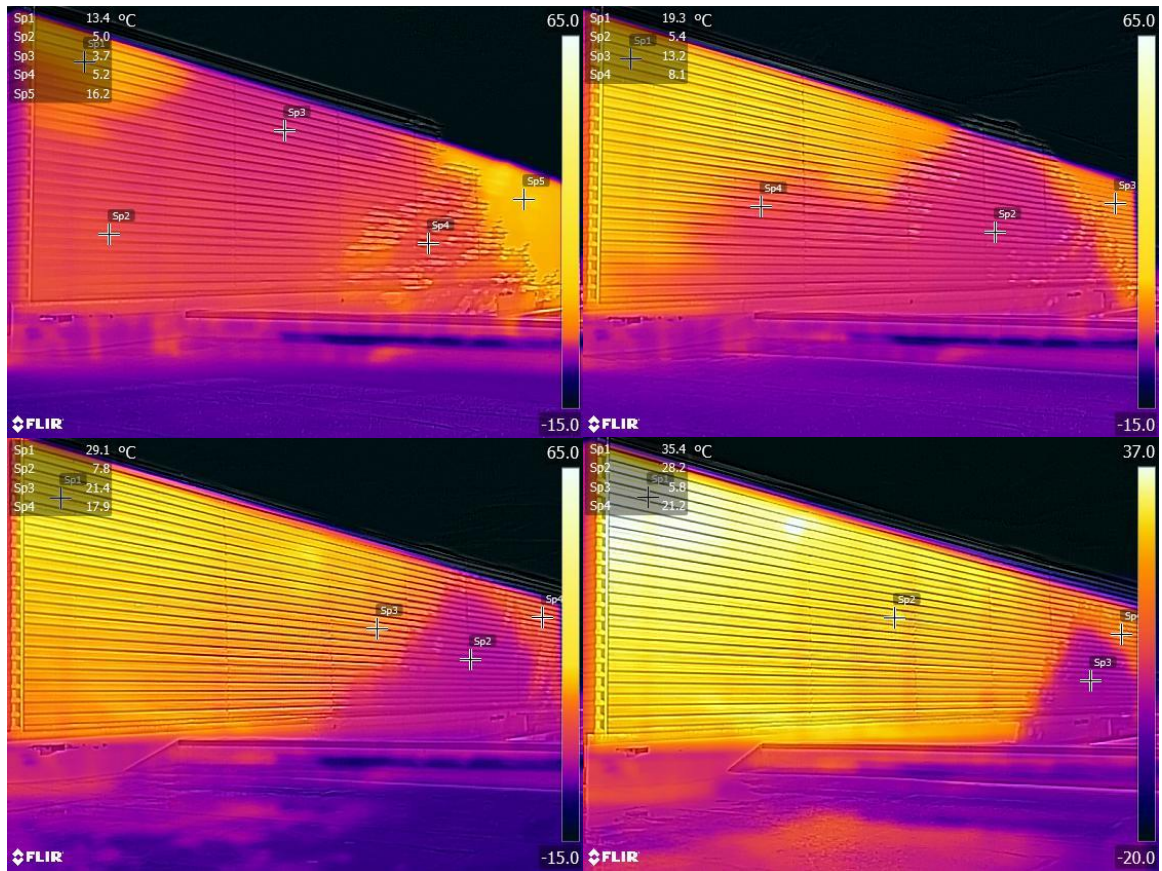


Figure 39: Thermal images for mesh study. Top left – 08:35. Top right – 09:05. Bottom left – 09:30. Bottom right – 10:35.

When comparing the linearly interpolated temperature profiles to the infrared images, it can be seen that the cavity profiles are a better representation of the temperature profile. The cold and hot areas of the cavity are in the correct general area and take on the same general shape as seen in the infrared images. More measurement points throughout the cavity would help improve this the accuracy of this temperature profile, but it can be said that the interpolated profile from the fine mesh and six measured points can be used as an estimate. However, this is not the case for the surface temperature profile. The high and low temperature points along the surface are not in the right locations and do not result in a similar profile. A first glance, it looks as if the

measured temperatures were in the wrong locations. Because of this a sensor location validation test was performed. As seen in Figure 40, an external heat source was applied to the sensor location. The temperature increase could be seen almost immediately for the surface sensors and after about a minute for the cavity sensors. This was done for all six locations and validated that the surface and cavity sensor locations were accurate. Knowing this reveals that the manner in which the surface temperatures are being measured results in inaccurate temperature profiles. This error propagated to the average surface temperature and through to the UTSC performance calculations.



Figure 40: Sensor location validation test

Distance Error of Infrared Camera

Due to the location of the UTSC in relation to the roof, all the infrared images for the thermography studies were taken at an angle. This leads to a dramatic difference in the perceived camera to object distance along the length of the UTSC. As the infrared images have been used throughout this study as a data and calculation verification method, it is important to evaluate the sensitivity of object distance on the temperature measured. Figure 41 is a sample calibrated infrared image taken on October 23rd at 10:35.

Four points of interest are marked on the surface of the UTSC and the temperature at those points is displayed on the image.



Figure 41: Infrared image of Jab's Hall UTSC 2015/10/23 10:35

The camera distance used when calibrating this image was 18.5 m (61 ft) or the average distance that the camera was from the UTSC surface. The temperatures are recorded at the four points of interest with this setting. Then the distance in the camera settings were adjusted to the maximum and minimum distance the camera was from the UTSC surface. The temperatures at the same four points were recorded for these two settings. These temperatures and associated errors from the calibrated, average camera distance are shown in Table 5. As seen in the table the object distance does affect the measured

temperature, however that affect is very small. Emissivity, atmospheric temperature and reflected temperature have a more substantial effect on the measured temperature.

Table 5: Evaluation of effect of object distance on infrared camera measurement, 2015/10/23 10:35

	Calibration Camera Distance 18.5 m (61 ft)	Maximum Camera Distance 25.5 m (84 ft)	Minimum Camera Distance 11.5 m (38 ft)	Larger Error From Average Camera Distance
Point 1	35.4°C (93.9°F)	35.5°C (94.1°F)	35.3°C (93.7°F)	0.3%
Point 2	28.2°C (82.8°F)	28.3°C (82.9°F)	28.1°C (82.6°F)	0.4%
Point 3	5.8°C (42.4°F)	5.8°C (42.4°F)	5.8°C (42.4°F)	0%
Point 4	21.2°C (70.2°F)	21.2°C (70.0°F)	21.1°C (70.0°F)	0.5%

Velocity Sensor Validation Test

The location of the AHU-A inlet duct velocity sensor was cause of concern.

Figure 42 is a schematic of the mechanical penthouse at Jabs Hall. The outlined section labeled A is the location of the inlet duct from the UTSC. The duct travels in the building less than 0.3 m (1 ft) before turning 90 degrees and traveling into AHU-A. The sensor is located 0.05 m (2 in) before this turn, in the center of the duct. This is a less than ideal location to measure the air velocity in a duct, due to the turbulent nature of the flow.

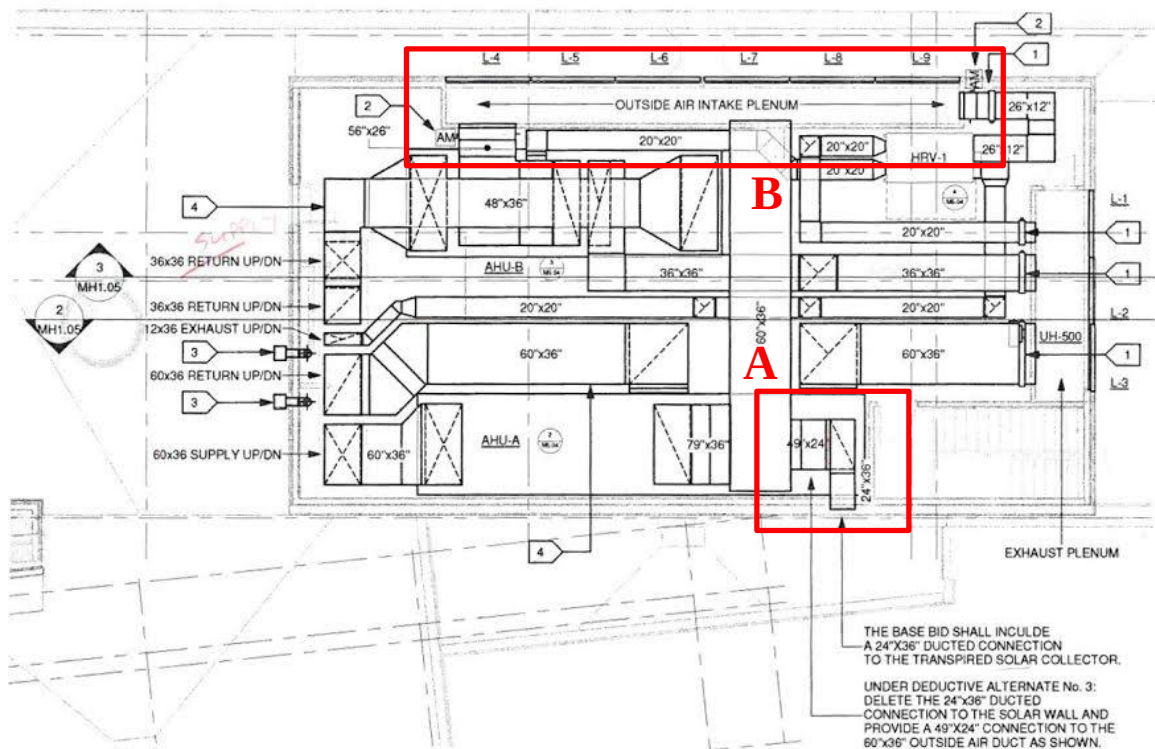


Figure 42: Schematic of mechanical penthouse at Jabs Hall. Highlighted section A is the inlet into AHU-A through the UTSC and section B is the UTSC bypass louver.

A velocity profile test was performed to verify the flow measurements at this point. This test was performed in the first week of October. The weather at this time did not require the use of the USTC so the building controls systems was overridden to force airflow through the USTC. In order to accomplish this, the UTSC intake damper was opened and the UTSC bypass damper, labeled as B in Figure 42, was closed. The supply fan speed was varied from 20% to 100% in 10% increments. Velocity measurements were taken at 24 points within the duct for each of these supply fan speeds, at 6 vertical positions and 4 horizontal positions. While these 24 velocity measurements were taken, the AHU-A velocity probe measurements were recorded every 5 seconds. With these measurements a

duct velocity profile was determined and could be directly compared to the point velocity measured from the AHU-A velocity sensor at multiple operation conditions.

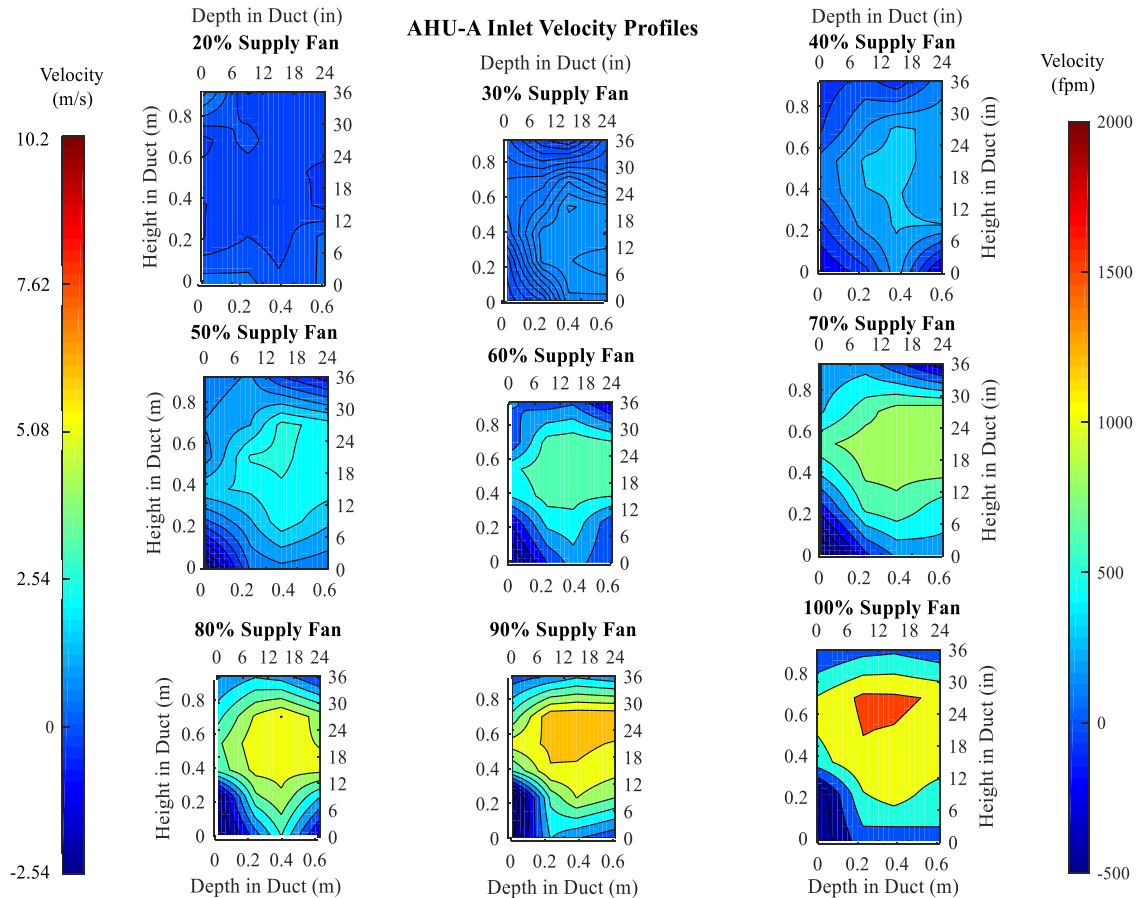


Figure 43: AHU-A inlet velocity profiles based on supply fan speed

One observation is that the center point of the duct, where the AHU-A velocity sensor is located, is always at a relatively high velocity value in the flow field. A calibration curve must be created to adjust the AHU-A velocity sensor measurement to more closely align with the actual overall duct velocity.

When performing this test, air was being forced through the USTC even though the VAV boxes served by AHU-A were not requiring air. This caused the pressure in the

supply duct to increase during the testing period to levels not experienced in typical operation. Table 6 outlines the static pressures both in the supply duct and in the building. During normal operation the velocity through the AHU is varied to keep the pressure in the supply duct and building the same. This was not the case during this test and could cause the calibrated velocity to be underestimated, especially at the higher velocity values.

Table 6: Pressure condition during AHU-A velocity profile test

Supply Fan Speed	Supply Duct Static Pressure	Building Static Pressure
40%	5.0 Pa (0.02 “H ₂ O)	5.0 Pa (0.02 “H ₂ O)
50%	22.4 Pa (0.09 “H ₂ O)	5.0 Pa (0.02 “H ₂ O)
60%	47.3 Pa (0.19 “H ₂ O)	5.0 Pa (0.02 “H ₂ O)
70%	67.3 Pa (0.27 “H ₂ O)	5.0 Pa (0.02 “H ₂ O)
80%	94.7 Pa (0.38 “H ₂ O)	5.0 Pa (0.02 “H ₂ O)
90%	137 Pa (0.55 “H ₂ O)	7.5 Pa (0.03 “H ₂ O)
100%	187 Pa (0.75 “H ₂ O)	7.5 Pa (0.03 “H ₂ O)

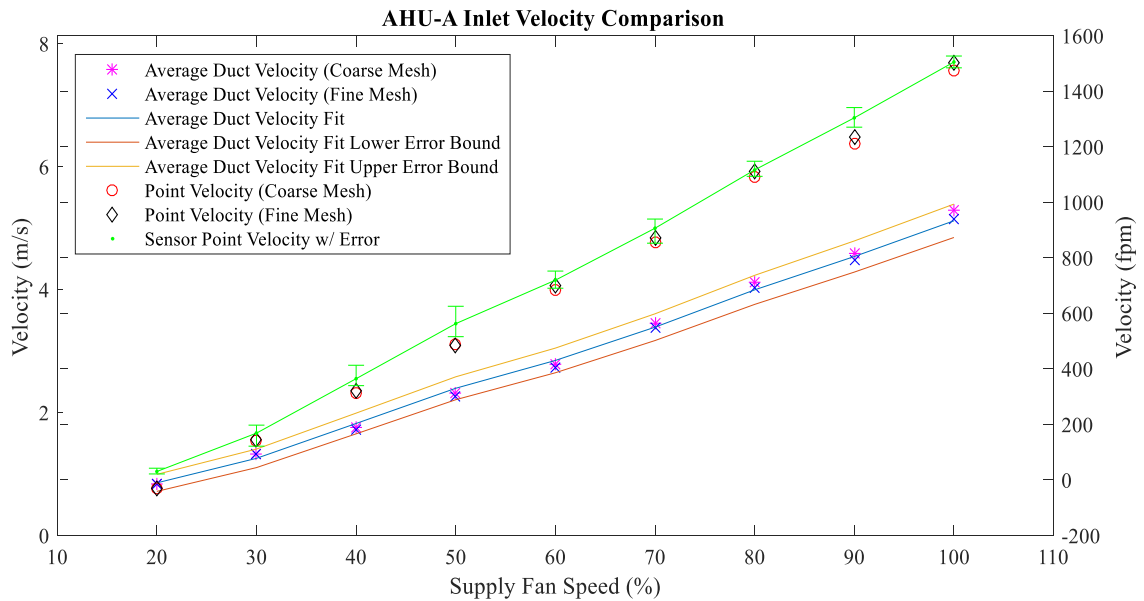


Figure 44: Velocity comparison from AHU-A velocity profile test

Figure 44 compares the results from the AHU-A velocity profile test. The green line with error bars are the AHU-A velocity sensor readings during the test. This is the installed sensor that needs to be calibrated. The pink star and blue cross are the resulting average duct velocity from the test using a coarse and fine rectangular mesh respectively. The blue line is the average duct velocity calibration curve applied to the calculations. The yellow line is the upper error bar and the red line is the lower error bar for this generated fit. The red circle and grey diamond are the point velocities for the location of the AHU-A velocity sensor using the average duct velocity profile for a coarse and fine mesh respectively. These should fall within the green AHU-A velocity sensor reading error bars. For the most part it does, some fall just below the lower error bar. Figure 45 compares the measured AHU inlet velocity to the calibrated velocity. It can be seen that

as the magnitude of the measured velocity increases, the difference between the measured and calibrated AHU-A velocities also increase.

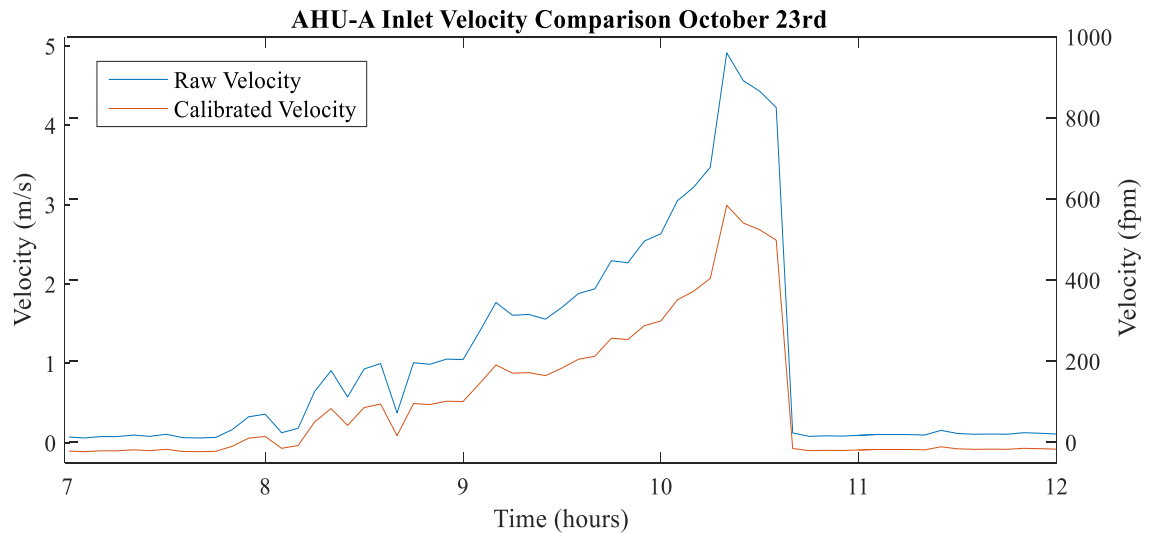


Figure 45: Comparison of measured and calibrated AHU inlet velocities

Sensor Uncertainty Analysis

Design-Stage Uncertainty Analysis of Sensor Data

The design-stage uncertainty for each sensor was determined using a root-sum-squares method which accounts for both the zero-order uncertainty due to resolution and instrument uncertainty. [23] For the uncertainty analysis for all the following sensors the uncertainty due to drift was not incorporated as the sensors had been deployed for less than a year for the duration of this study and the drift values were included were on a yearly basis. MATLAB functions were created for all deployed sensors to calculate the design-stage uncertainty for each sensor based off of the appropriate factors. For instance, the design-stage uncertainty for the solar irradiance sensor is dependent on both the

outdoor air temperature and the measured irradiance. The specification sheets for all sensors are included in Appendix F. The specification sheets list all the contributions to the design-stage uncertainty for the given sensor.

Calculation Uncertainty Analysis

When performing calculations, the uncertainty of each individual measurement is propagated through the calculation. The root sum squares method was used to evaluate the design-stage uncertainty of the measured values' contribution to the calculation uncertainty. [23] This includes error due to resolution, accuracy and operating conditions of the sensor but did not include an estimation of the error related to how and where the data was collected. The resulting uncertainties from this analysis for both the efficiencies and effectiveness calculations were smaller than the required uncertainty to make the results valid (i.e. efficiency values less than one or 100% efficiency). This uncertainty indicates that the dominant source of error is the data collection method. Characterization of potential error and alternate collection strategies should be a focus of future work

Field Study Results

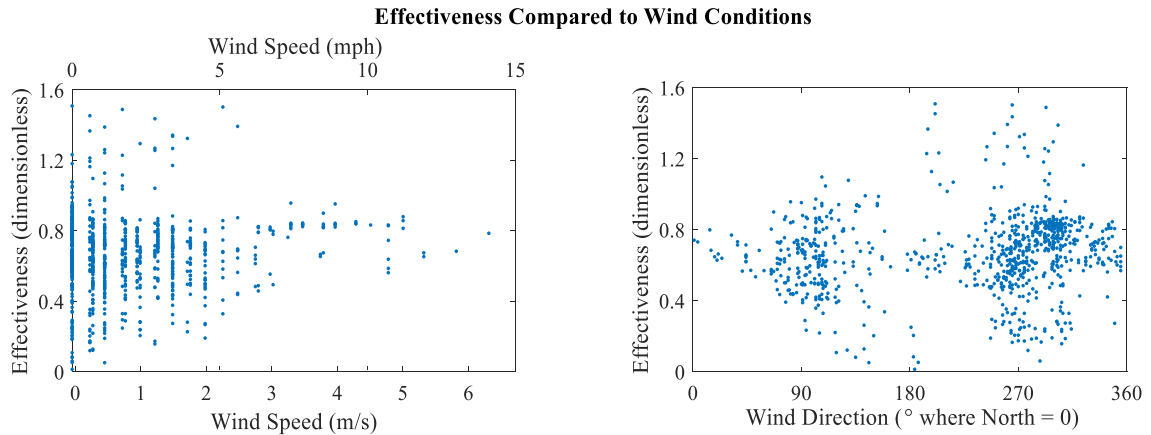


Figure 46: Heat exchange effectiveness compared to wind conditions. Left – wind speed vs. effectiveness. Right – wind direction vs. effectiveness.

Figure 46 shows, from field study data, how wind conditions affect heat exchange effectiveness of the UTSC. The wind speed plot is difficult to draw decisive conclusions from yet because at first glance it appears as if effectiveness increases with increasing wind speeds. However, there are far fewer data points at the higher wind speeds. It can be seen that at the lower wind speeds there is a great concentration of points at higher effectiveness levels. More data points at higher wind speeds would help see the true effect of elevated wind speeds on heat exchange effectiveness. Also from Figure 46, it can be observed that effectiveness decreases at the shear directions for the UTSC, 90° and 270° which is the prevailing east and west winds. Also noteworthy are the heat exchange effectiveness values above one, which is theoretically impossible. Heat exchange effectiveness is a function of temperature alone. As discussed previously, the amount of sample points along the surface and in the cavity of UTSC does not

completely capture the effect that shading has on the temperature profiles of the UTSC.

The effect of this can be observed as skewed heat exchange effectiveness values.

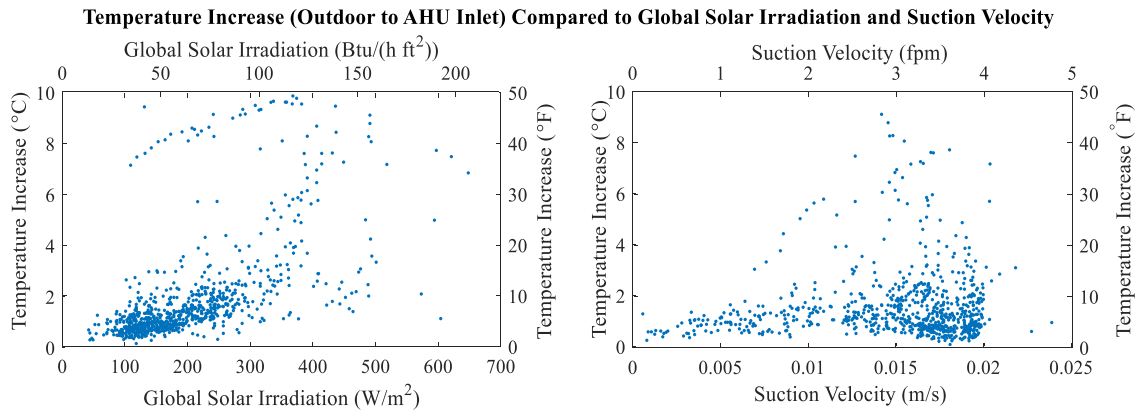


Figure 47: Temperature increase (from outdoor air to AHU-A inlet) compared to global solar irradiance (left) and suction velocity (right).

Figure 47 shows one of the more compelling trends observed from the data set. It is seen that temperature increase, from the outdoor air to the AHU inlet, is larger with increasing solar irradiance. The effect that the suction velocity has on the temperature increase is also shown. There is a concentration of low temperature increase at the higher range of suction velocities. Looking at both parts of Figure 47 indicates that while suction velocity is an important design parameter, the performance is more strongly related to solar irradiance. For a designer in industry this shows the importance of placing an UTSC in a location with little to no solar obstructions. If the sun isn't shining on the UTSC, there isn't a potential to be collecting free energy. It is important to understand how these other variables – such as wind – affect the performance in order to appropriately size the UTSC and keep suction velocities low. A wind rose will be an important tool to help understand wind characteristics.

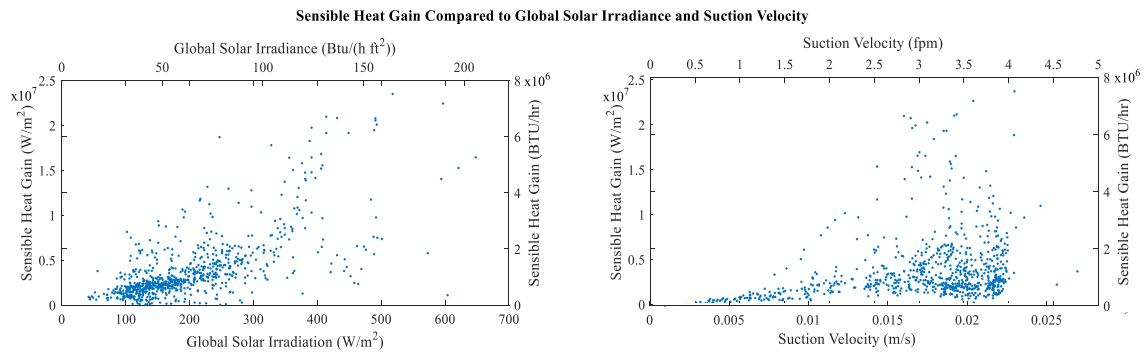


Figure 48: Sensible heat gain compared to solar irradiance and suction velocity

In Figure 48, the sensible heat gain comparison to global solar irradiance continues to reinforce the previous discussion. The suction velocity comparison in Figure 48 doesn't have as compelling relationship. It is apparent that the lower values of sensible heat gain correspond to low solar irradiance and these low solar irradiance values occurred with various suction velocities. The higher sensible heat gains correspond to higher levels of solar irradiance occurring at varying suction velocities. Collecting more data points at low suction velocities and higher levels of solar irradiance might result in a more compelling trend for suction velocity.

Comparison to Energy Model

When first looking at the results of the energy model there was a major difference in the suction flow rates across the UTSC. The energy model was over predicting the demand on AHU-A and thus yielding in higher suction flow rates across the board when compared to the field study data. This could be caused by any number of input loads and schedules. The loads in the building were specified according to energy standards. The building is probably not currently experiencing full loading conditions which would

account for how the AHU is being over utilized in the model. After a full year of utility data is collected on the building it would be beneficial to use that information to calibrate the model. This model calibration process is an important step to have the energy model tuned and have it behave more like the actual building.

Figure 49 shows the solar irradiance comparison between the collected data and model results on November 5th. The blue line is the global solar irradiance data collected. This data was collected every five minutes. The red line is the global solar irradiance values entered into the energy model. The energy model takes values every hour, so that is why these data sets look different. It is the same data with different time resolutions applied. The yellow line is the solar irradiance experienced by the UTSC in the energy model. These values are larger than the global solar irradiance entered into the energy model but follow the same trend. In the winter months when the sun is at its lowest angle, the global – vertical measured component of – solar irradiance would be smaller than the horizontal component of the normal solar irradiance – which is what the UTSC is experiencing. The trend in Figure 49 makes sense. This also illustrates the importance of characterizing more than one solar irradiance component for the purposes of the field study. The global irradiance term was used in the field study calculations, however in the winter months the solar irradiance falling on the surface could be more than this global irradiance value. This along with the error associated with the temperature profile explain the large unrealistic efficiency values calculated from the field study data.

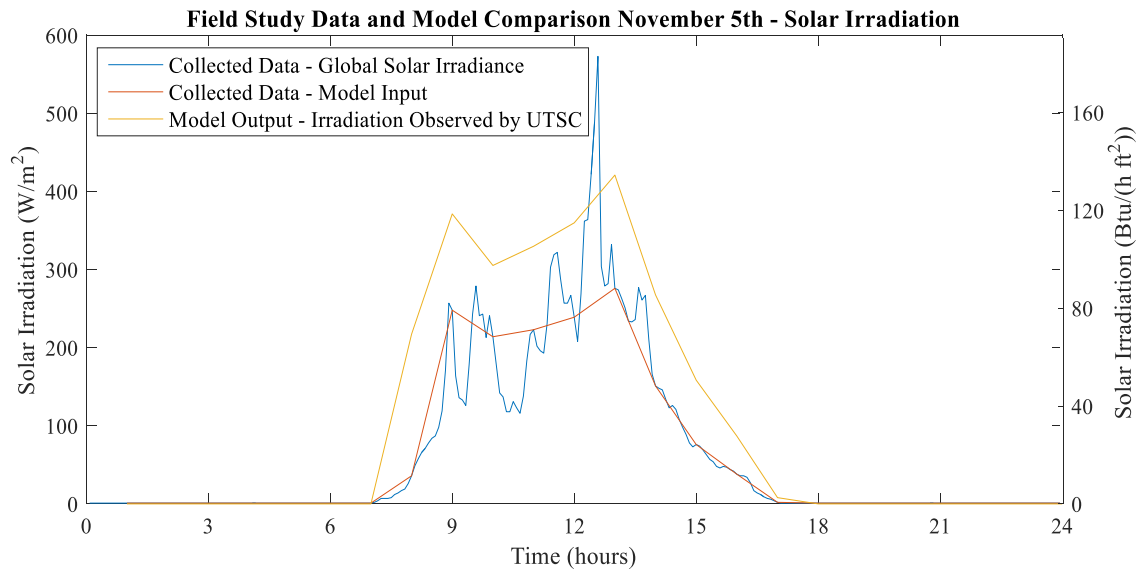


Figure 49: Comparison of field study data to model result, solar irradiance

Figure 50 compares field study data to modeled AHU inlet temperatures on November 5th. The blue lines are the collected AHU inlet temperatures on a five minutes interval. The red line is also temperature data but with an hour time step applied. This curve would be a more realistic output for a calibrated energy model to follow. The yellow line is the model output for the AHU inlet temperature. Because the model has suction flow rates higher than experienced in the field study, the AHU inlet temperature will be lower when compared to the field study data. However, it is encouraging that the model results follow a similar trend to the collected field study data. Another encouraging result is that when the same energy model was run with and without the tree shading object there was a difference in predicted total sensible heating energy over the simulated year; the shading object created a 10% decrease in total sensible heating energy over a year. Although the field study results do not perfectly align with the energy model results, the results are indicating that a calibrated energy model could predict the performance of

an UTSC especially when taking into consideration solar obstructions and shading objects.

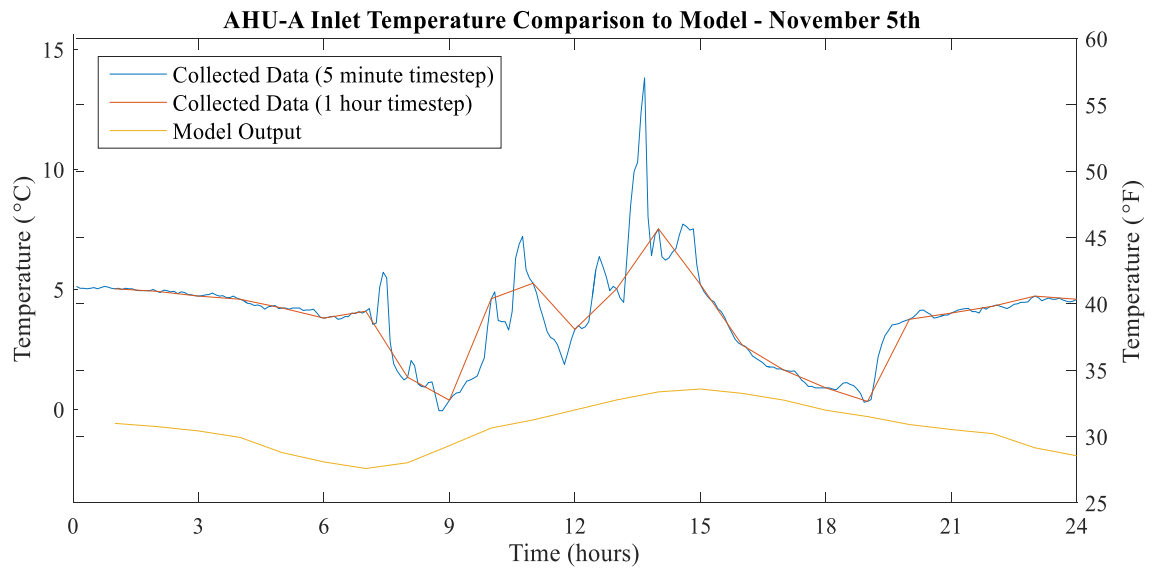


Figure 50: Comparison of field study data to model result, AHU inlet temperature

CONCLUSION

Field study data was collected on the Jabs Hall UTSC and analyzed first independently and then in comparison to an energy model. The energy model, created in a commercially available software, incorporated both the building and the UTSC. The modeled UTSC did not behave in the same manner as the field study data, and this was more due to how the building was modeled and not the UTSC model component itself. To validate this, future work will need to be performed that is explained in the following section. Another outcome of this work was analyzing how the UTSC incorporates into the building HVAC system. A critical look was taken on how to optimize energy recovery from the UTSC. This is discussed in the following section titled “Importance of System Integration”.

Recommendations for Future Work

Energy Model Calibration

At the time of this research, Jabs Hall was a new building; there wasn't historical utility data available. The building was still in its first few months of operation and system controls were still being optimized. Building drawing sheets and energy standards were used to approximate the characteristics of the building. However, these assumptions do not accurately represent the building operation during this research. After a year or more of building operation, there will be better understanding of how the building actually is used and operated, not just how it was designed to operate. With this information, the energy model should be revisited and calibrated to a year of utility data.

[24] A calibrated model that behaves more like the actual building would result in more comparable data.

Verification of AHU Velocity Profile

It is recommended to perform the AHU velocity profile test again during actual winter operating conditions and when the UTSC is actually being used naturally by the building. There are holes already drilled in the AHU inlet duct. One should take measurements periodically throughout the day to get the flow profile at different flow rates but under actual operating conditions. Doing this would create a better quality calibration curve for the AHU inlet duct velocity measurement.

Improve Temperature Profiles

One of the largest sources of error in this work is related to more accurately characterizing the surface temperature profiles. This value is important for UTSC performance calculations. When solar obstructions for the UTSC exist, such as trees or other buildings, characterizing the surface temperature profile becomes even more critical. When considering future improvements for this, the answer isn't simply more sample points along the surface of the UTSC. Of course, more sample points will help but there is a trade off with maintainability and feasibility of deploying the data acquisition system in the field. A simple solar site analysis should be performed at various lengths and heights along the UTSC to optimize the sensor grid locations to be able track shadows during various times of the year. Then one could use a shadowing software to better understand and track the shadow along the UTSC surface. This could

be overlaid with the point temperature measurements to better estimate the UTSC surface temperatures.

Understanding “Global Geometry”

One parameter not incorporated in the UTSC energy model component is the inlet duct size and location in the wall. In all the thermography studies, located in Appendix A through Appendix D, the west third of the UTSC surface consistently is warmer than the rest of the wall. This indicates that the air is not being evenly drawn through the UTSC surface and that this portion of the UTSC is being shorted. This indicates the inlet duct, size and location, is a parameter that changes the airflow characteristics through the UTSC. What is going to be referred to as “global geometries” such as inlet duct size and location in relation to the overall orientation of the UTSC (horizontal or vertical), corrugation orientation, size of the UTSC and shading characteristics affect the airflow and heat transfer characteristics. Design engineers in industry implementing a UTSC have to primarily define these “global geometries” and yet the design tools do not reflect this. There is a design tool that can flow distribution through transpired solar collectors, however the major limitation is that the inlet duct is modeled on the top edge of the plenum only. [25] A design tool that integrated the effect of “global geometries” on flow through the UTSC with the standard effectiveness correlations would be useful in industry.

Importance of System Integration

An important observation from the raw data shown in Appendix E is that the UTSC is being underutilized in the shoulder seasons and even the heating season. The VAV with reheat system that the UTSC is integrated into requires 13°C (55°F) air to be conditioned in the AHU. If required, the VAV box at the point of use will reheat the air. If the air leaving the UTSC is above this set point, the UTSC is bypassed and air is drawn in through the north intake louver, regardless of the heating demands within the building. This characteristic or system optimization choice limits the potential free energy that can be harvested from the UTSC. Looking through Appendix E, it can be seen that this is a common theme. A more holistic look needs to be taken during the system selection and control optimization processes to maximize the free energy that can be collected from the UTSC. A recommendation to remedy this issue at Jabs Hall in a cost effective manner would be to eliminate the on/off characteristic. When the air temperature leaving the UTSC is above set point, modulate and mix air from the north intake louver to reach temperature set point instead of completely bypassing the UTSC.

In future UTSC installations, it would be recommended to tie the UTSC into a system that is more likely to accept that energy. A proposed system would be to integrate the UTSC into a heat pump based dedicated outdoor air system. In the Bozeman, Montana climate and most climates where the installation of a UTSC would be beneficial, the building can use all possible free energy. If the air stream doesn't need the energy, the heat pump can be run in reverse to cool the air to the appropriate temperature. The energy extracted from the air would be put into the building source water loop. This

energy can be used elsewhere in the building that requires it. If the source water loop was integrated into a geothermal loop, that extra energy could be stored in the ground until it was needed. The elegance of this implementation is that it maximizes the energy harvested from the UTSC in the shoulder and heating seasons. If the UTSC is too ineffective at collecting heat for the air stream, this system effectively turns the UTSC into a cost-effective solar thermal collector. Preliminary calculations from the limited collected dataset imply that if this particular solar collector was optimized appropriately there is a potential to offset up to 20 metric tons of CO₂ on an annual basis [26]. This analysis should be revisited after a year of performance data has been collected. The optimized installation and monitoring of unglazed transpired solar collectors in sunny, heating dominated climates are a great thermal resource for the commercial building industry.

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APPENDICES

APPENDIX A

THERMOGRAPHY STUDY: OCTOBER 5TH, 2015

The first thermography study was performed on October 5th, 2015. Eight infrared images were taken starting at 07:26 and ending at 11:06. Figure 51 highlights the weather and AHU-A inlet conditions on October 5th. Table 7 outlines the infrared camera settings used for each photo taken of the thermography study.

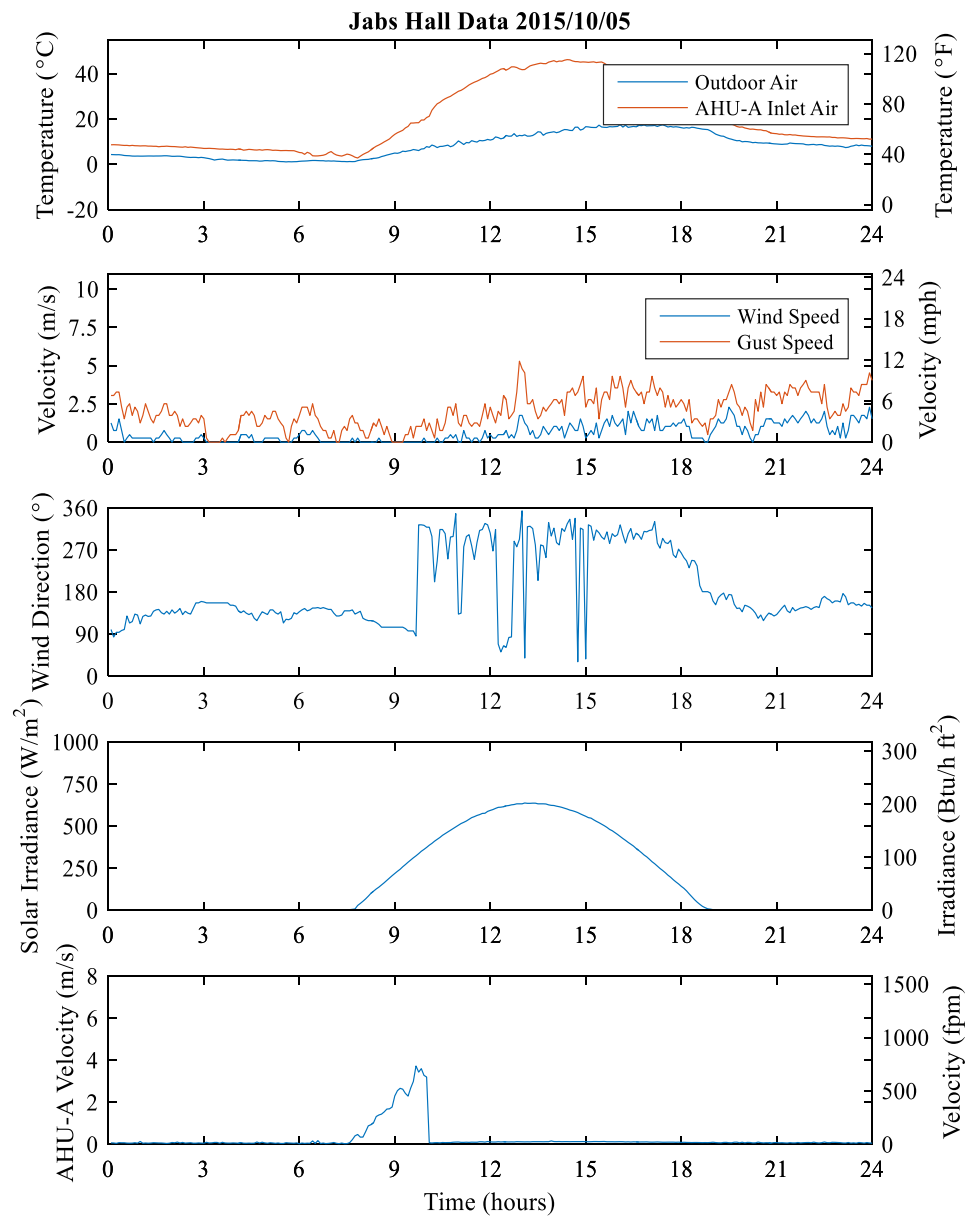


Figure 51: Weather conditions during the first thermography study on 2015/10/05

Table 7: Setting used in October 5th thermography study

Time	Atmospheric Temperature	Relative Humidity	Reflected Temperature
07:26	1.67°C (35°F)	90%	-6.11°C (21°F)
07:55	1.67°C (35°F)	88%	-2.22°C (28°F)
08:21	2.78°C (37°F)	85%	0°C (32°F)
08:48	2.89°C (39°F)	80%	0°C (32°F)
09:20	5.56°C (42°F)	76%	0°C (32°F)
10:01	7.78°C (46°F)	72%	11.1°C (52°F)
10:30	7.78°C (46°F)	69%	12.8°C (55°F)
11:06	10.0°C (50°F)	66%	14.4°C (58°F)

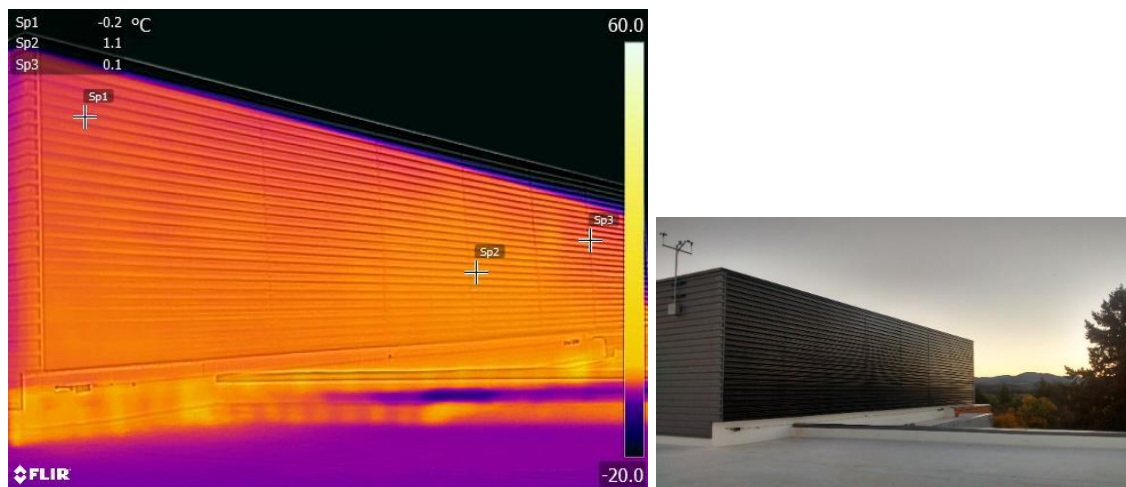


Figure 52: Jabs Hall UTSC 2015/10/05 07:26

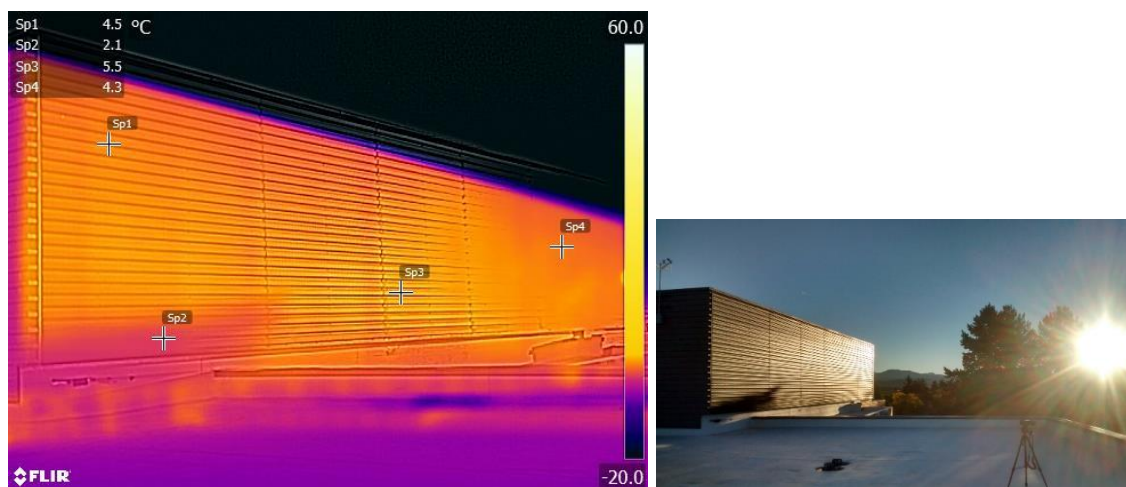


Figure 53: Jabs Hall UTSC 2015/10/5 07:55

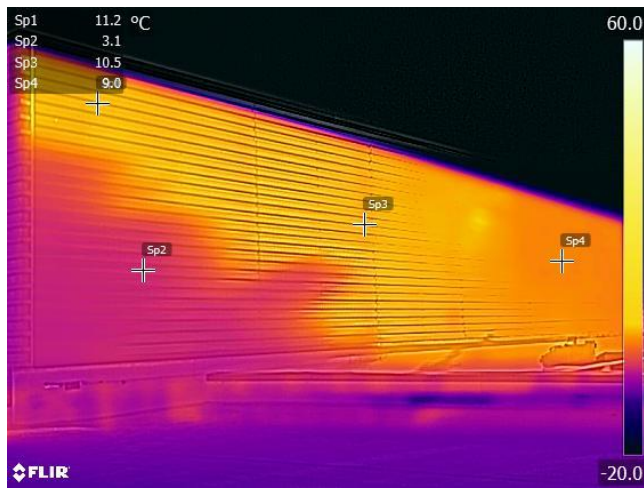


Figure 54: Jabs Hall UTSC 2015/10/5 08:21

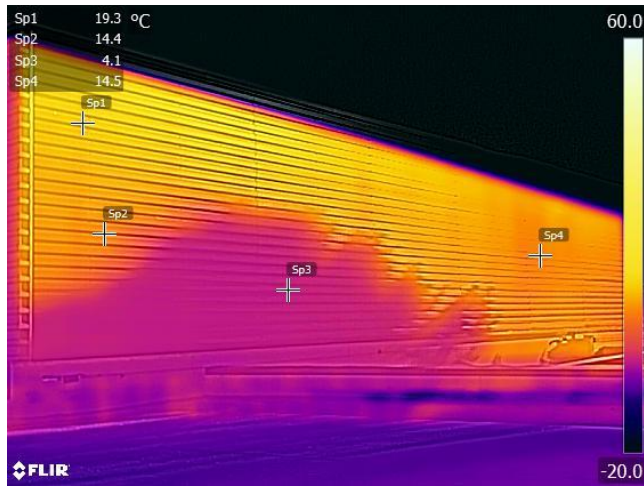
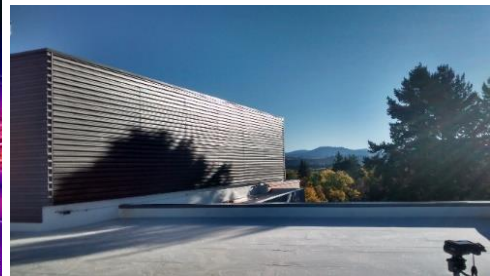


Figure 55: Jabs Hall UTSC 2015/10/5 08:48



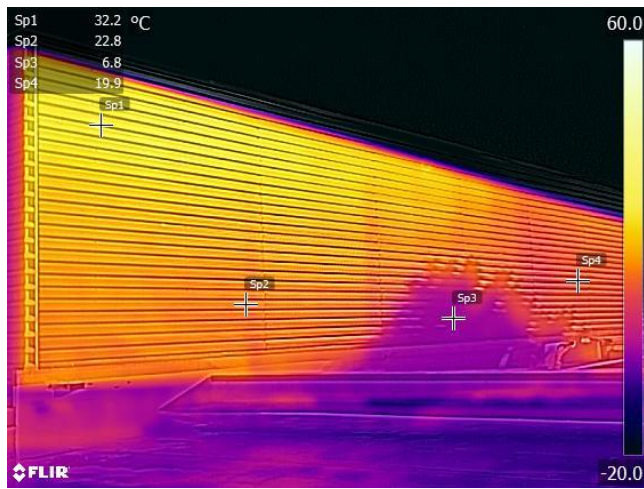


Figure 56: Jabs Hall UTSC 2015/10/5 09:20

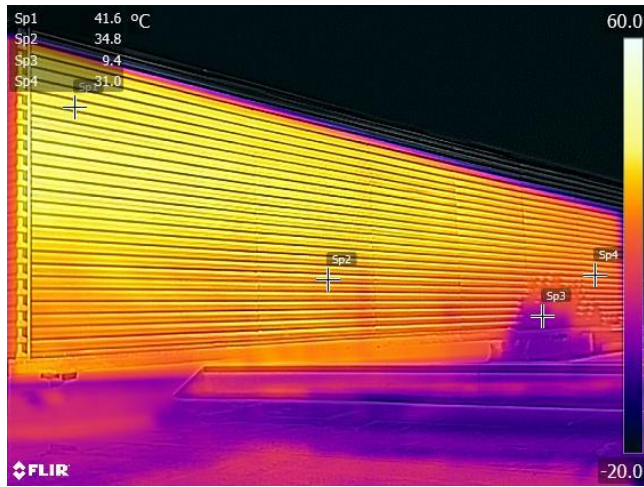


Figure 57: Jabs Hall UTSC 2015/10/05 10:01

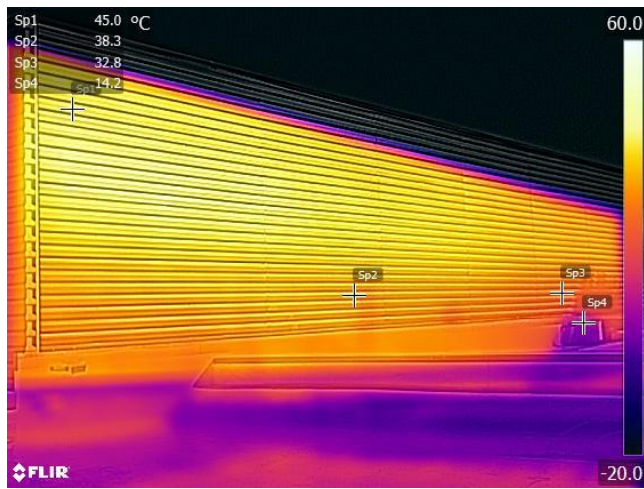


Figure 58: Jabs Hall UTSC 2015/10/05 10:30

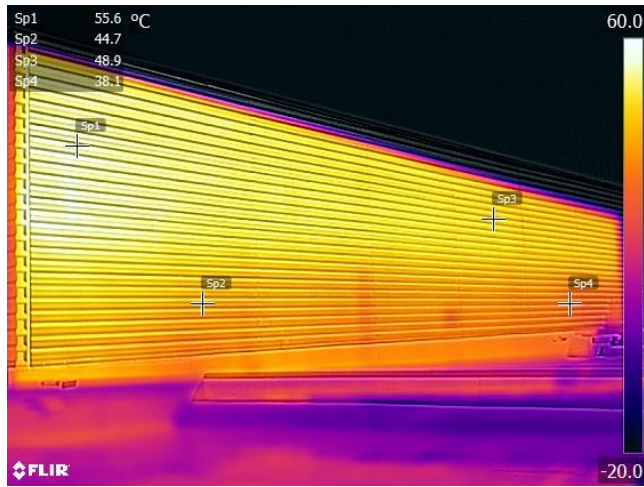


Figure 59: Jabs Hall UTSC 2015/10/05 11:06



APPENDIX B

THERMOGRAPHY STUDY: OCTOBER 23RD, 2015

The second thermography study was performed on October 23rd, 2015. Eight infrared images were taken starting at 08:08 and ending at 12:00. Figure 60 highlights the weather and AHU-A inlet conditions on October 23rd. Table 8 outlines the infrared camera settings used for each photo taken of the thermography study.

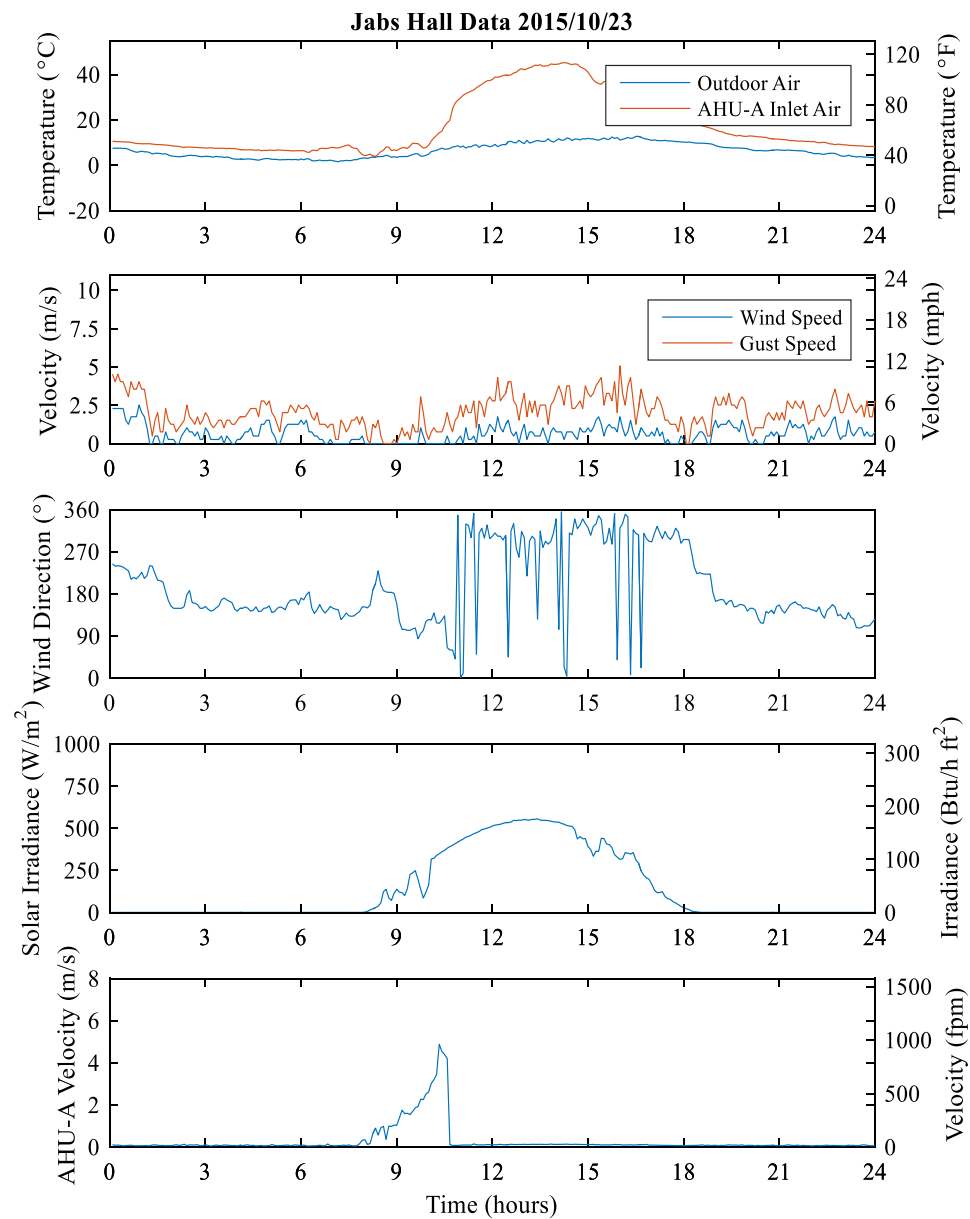


Figure 60: Weather conditions during the second thermography study on 2015/10/23

Table 8: Settings used in October 23rd thermography study.

Time	Atmospheric Temperature	Relative Humidity	Reflected Temperature
08:08	°C (38°F)	39%	°C (18°F)
08:35	°C (39°F)	75%	°C (33°F)
09:04	°C (39°F)	77%	°C (35°F)
09:30	°C (40°F)	73%	°C (51°F)
10:00	°C (41°F)	73%	°C (55°F)
11:05	°C (46°F)	61%	°C (62°F)
11:35	°C (48°F)	57%	°C (80°F)
12:00	°C (47°F)	58%	°C (68°F)

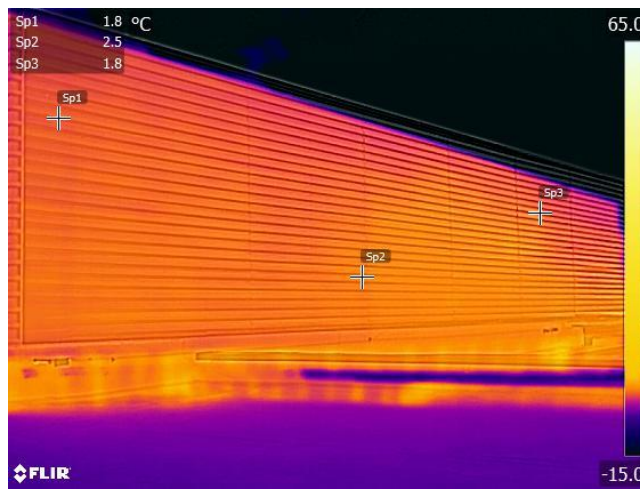


Figure 61: Jabs Hall UTSC 2015/10/23 08:08

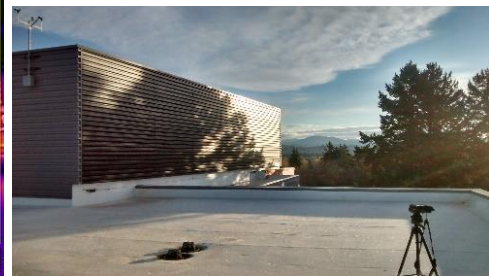
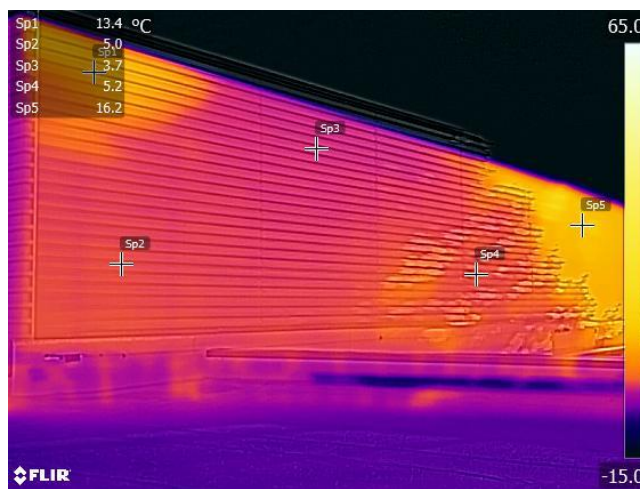


Figure 62: Jabs Hall UTSC 2015/10/23 08:35

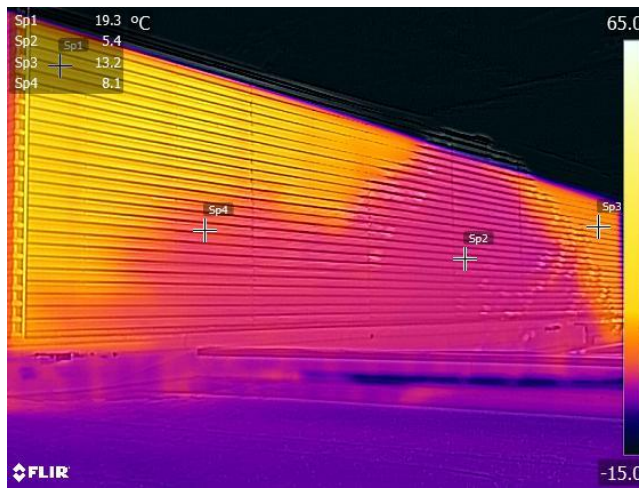


Figure 63: Jabs Hall UTSC 2015/10/23 09:04

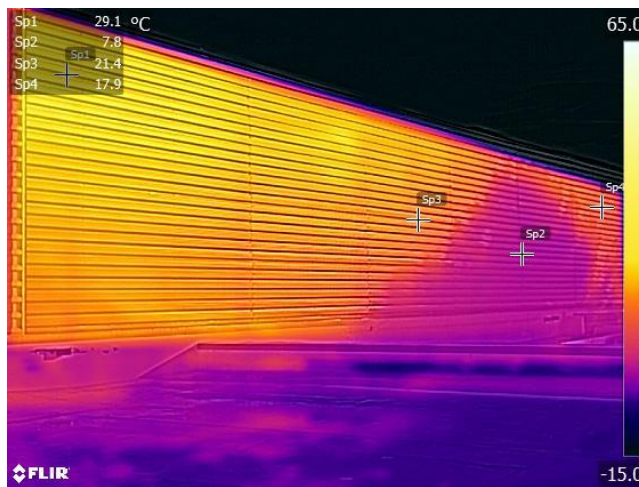
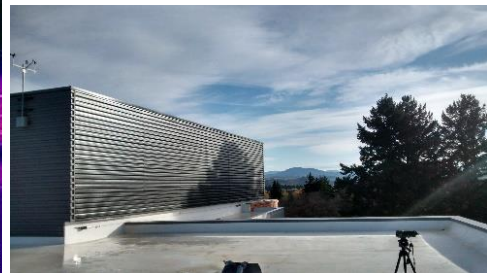


Figure 64: Jabs Hall UTSC 2015/10/23 09:30



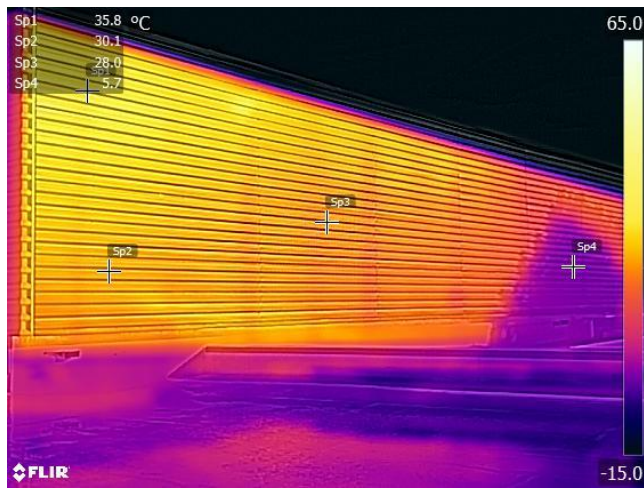


Figure 65: Jabs Hall UTSC 2015/10/23 10:00

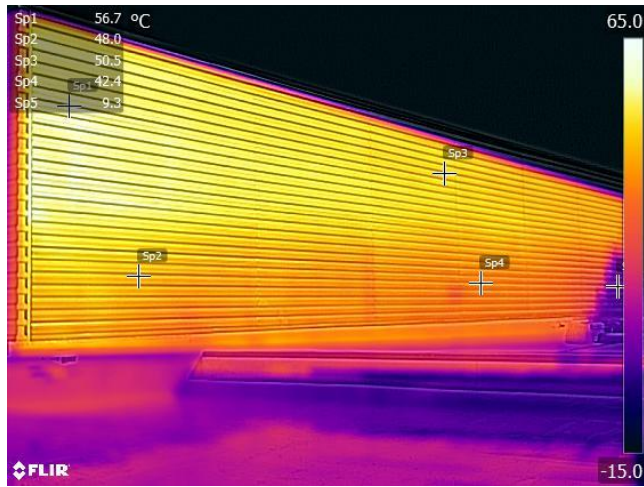


Figure 66: Jabs Hall UTSC 2015/10/23 11:05



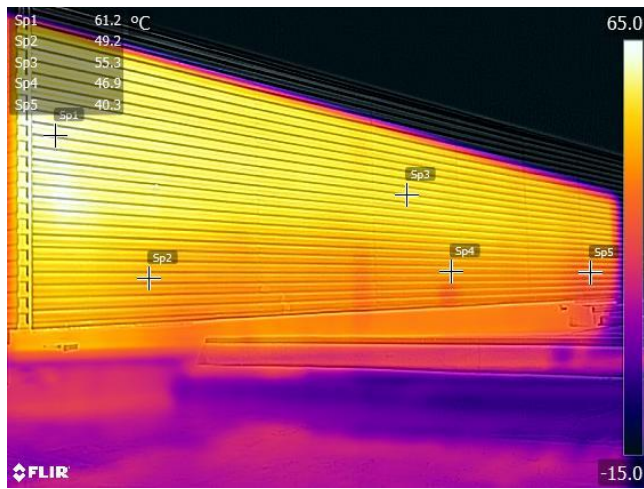


Figure 67: Jabs Hall UTSC 2015/10/23 11:35

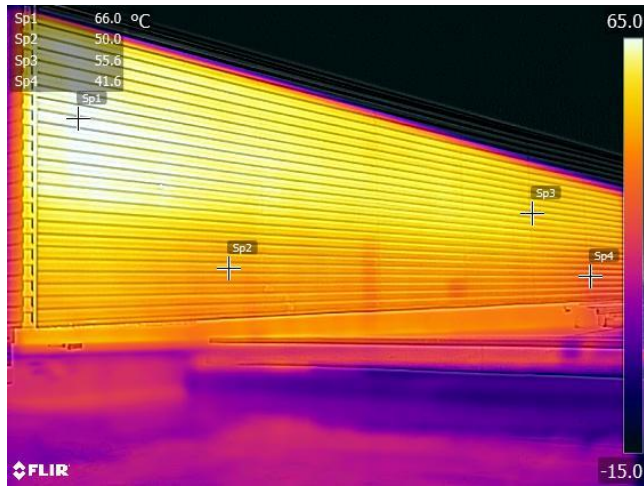


Figure 68: Jabs Hall UTSC 2015/10/23 12:00



APPENDIX C

THERMOGRAPHY STUDY: NOVEMBER 4TH, 2015

The third thermography study was performed on November 4th, 2015. Seven infrared images were taken starting at 07:25 and ending at 16:45. Figure 69 highlights the weather and AHU-A inlet conditions on November 4th. Table 9 outlines the infrared camera settings used for each photo taken of the thermography study.

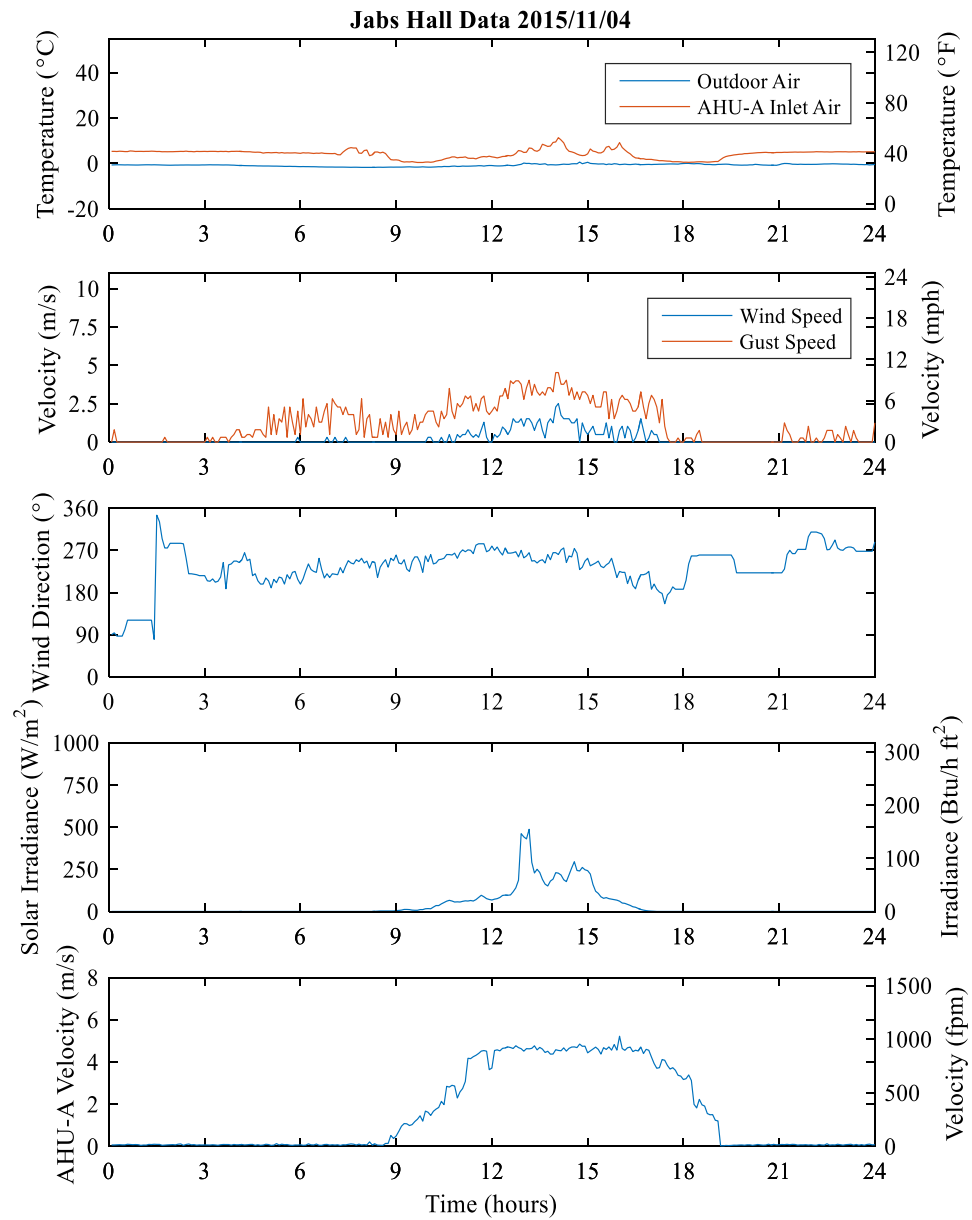


Figure 69: Weather conditions during the third thermography study on 2015/11/04

Table 9: Settings used in November 4th thermography study.

Time	Atmospheric Temperature	Relative Humidity	Reflected Temperature
07:25	0°C (32°F)	98%	°C (33°F)
09:12	°C (34°F)	97%	°C (35°F)
11:00	°C (34°F)	96%	°C (35°F)
12:50	°C (34°F)	96%	°C (35°F)
14:50	°C (33°F)	96%	°C (23°F)
15:44	°C (32°F)	88%	°C (27°F)
16:45	°C (32°F)	96%	°C (33°F)

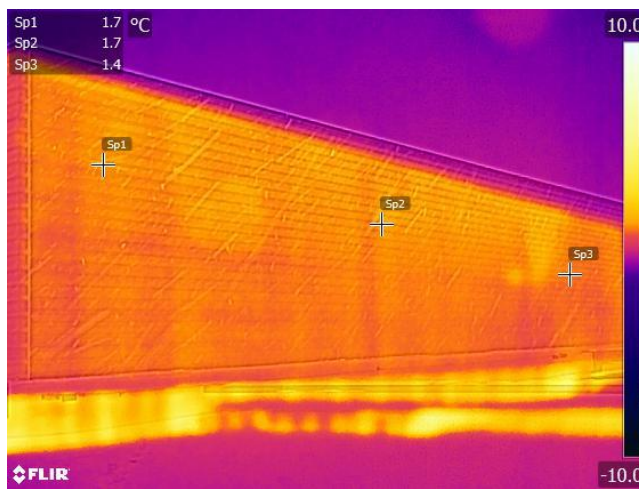


Figure 70: Jabs Hall UTSC 2015/11/04 07:25

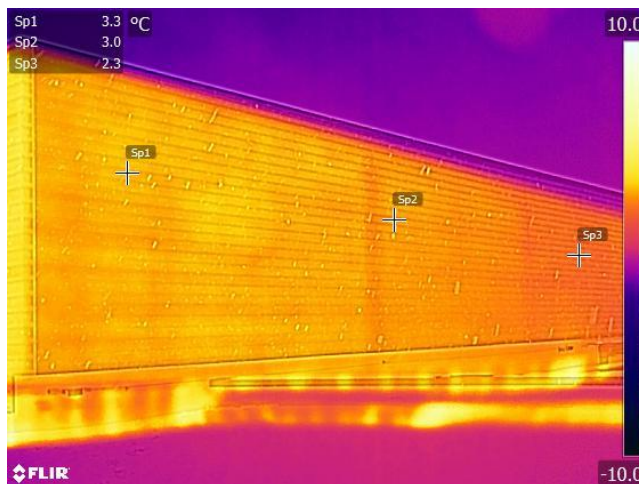


Figure 71: Jabs Hall UTSC 2015/11/04 09:12

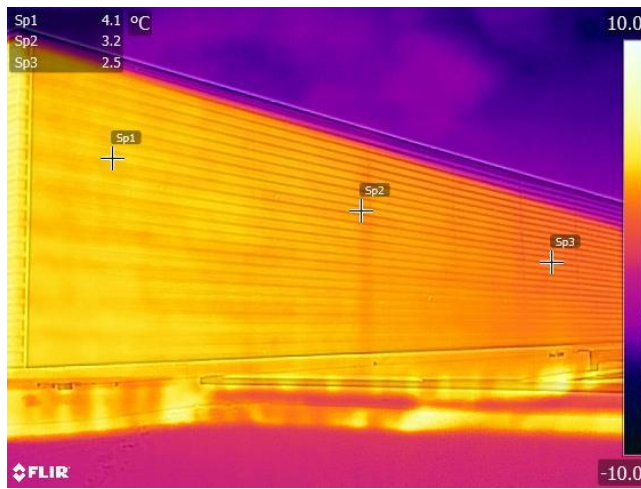


Figure 72: Jabs Hall UTSC 2015/11/04 11:00

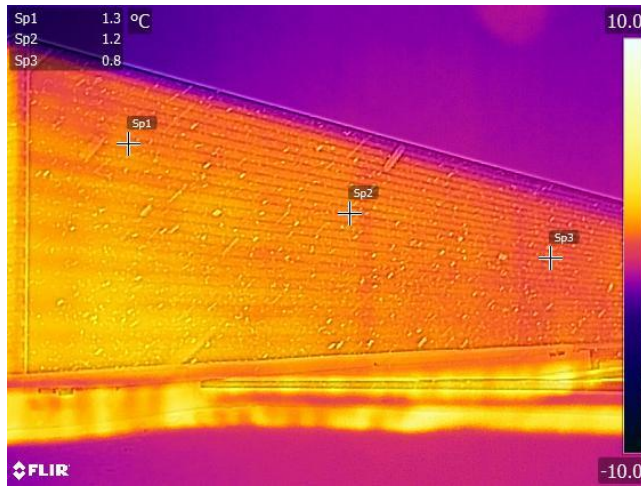


Figure 73: Jabs Hall UTSC 2015/11/04 12:50



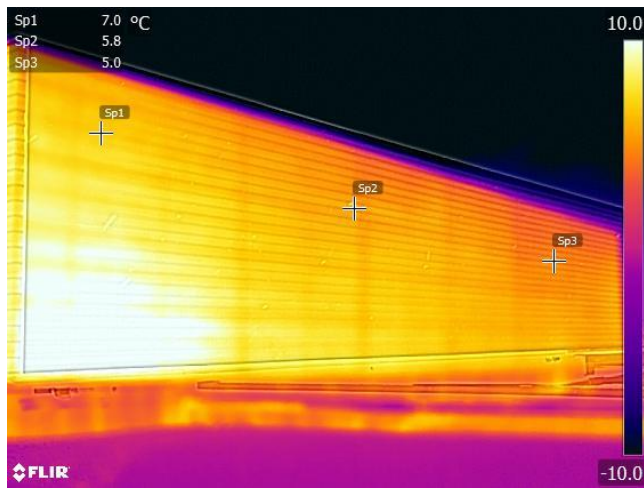


Figure 74: Jabs Hall UTSC 2015/11/04 14:50

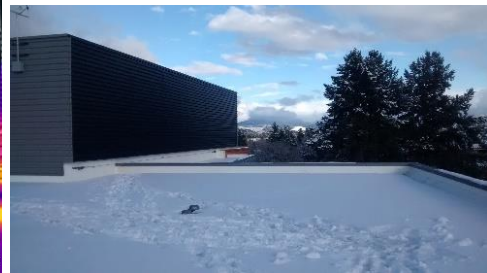
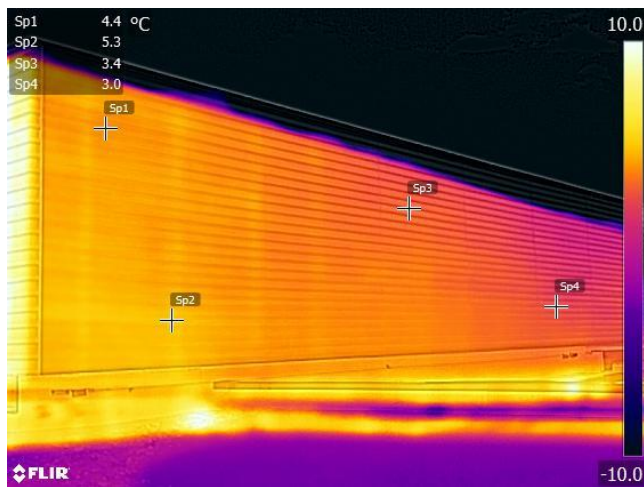


Figure 75: Jabs Hall UTSC 2015/11/04 15:44

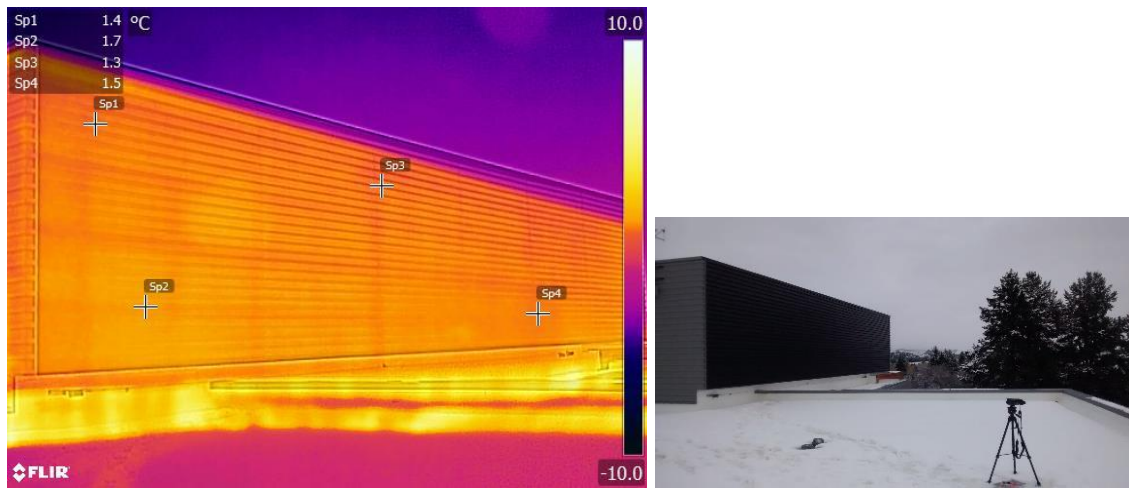


Figure 76: Jabs Hall UTSC 2015/11/04 16:45

APPENDIX D

COLLECTED RAW DATA

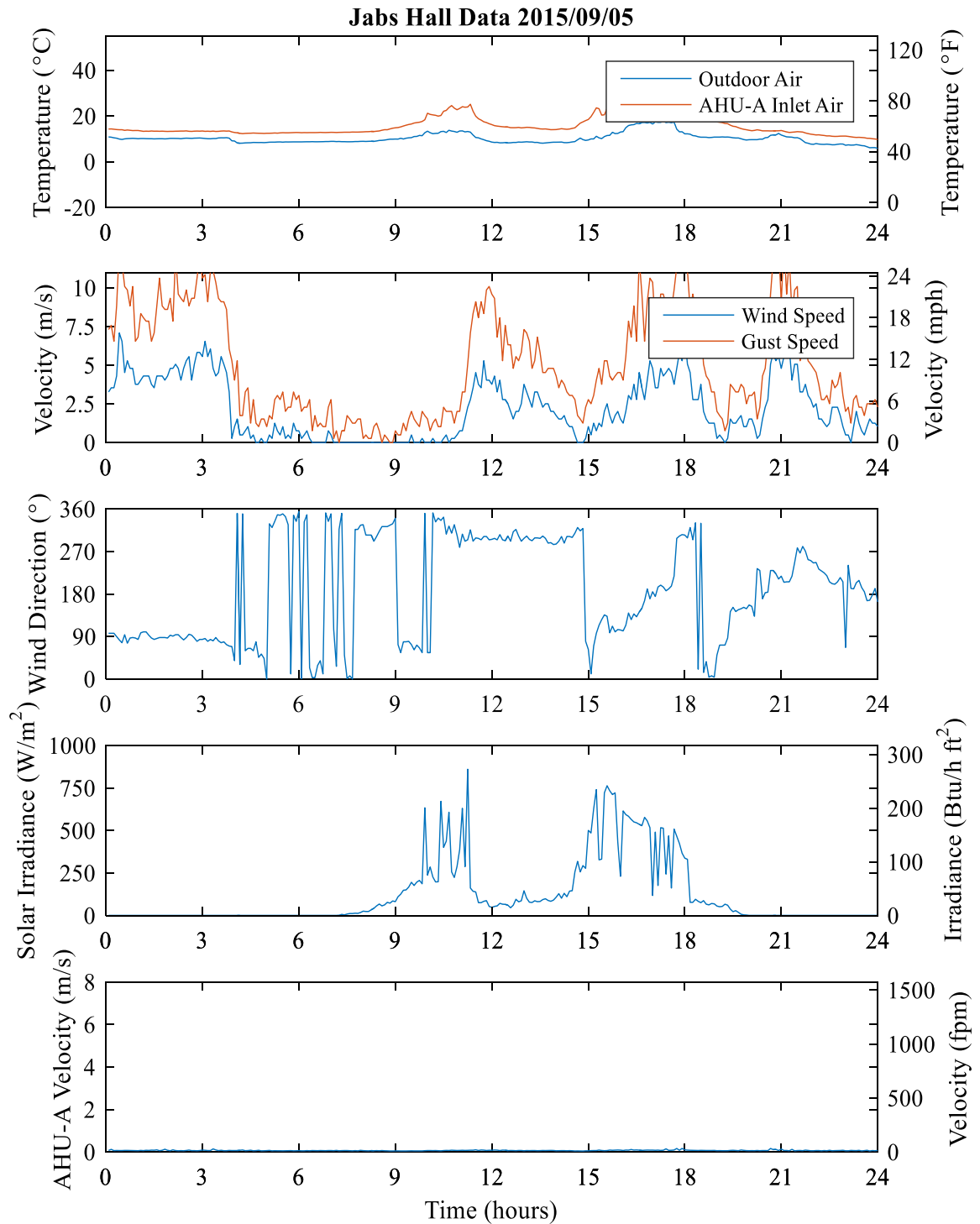


Figure 77: Jabs Hall Raw Data 2015/09/05

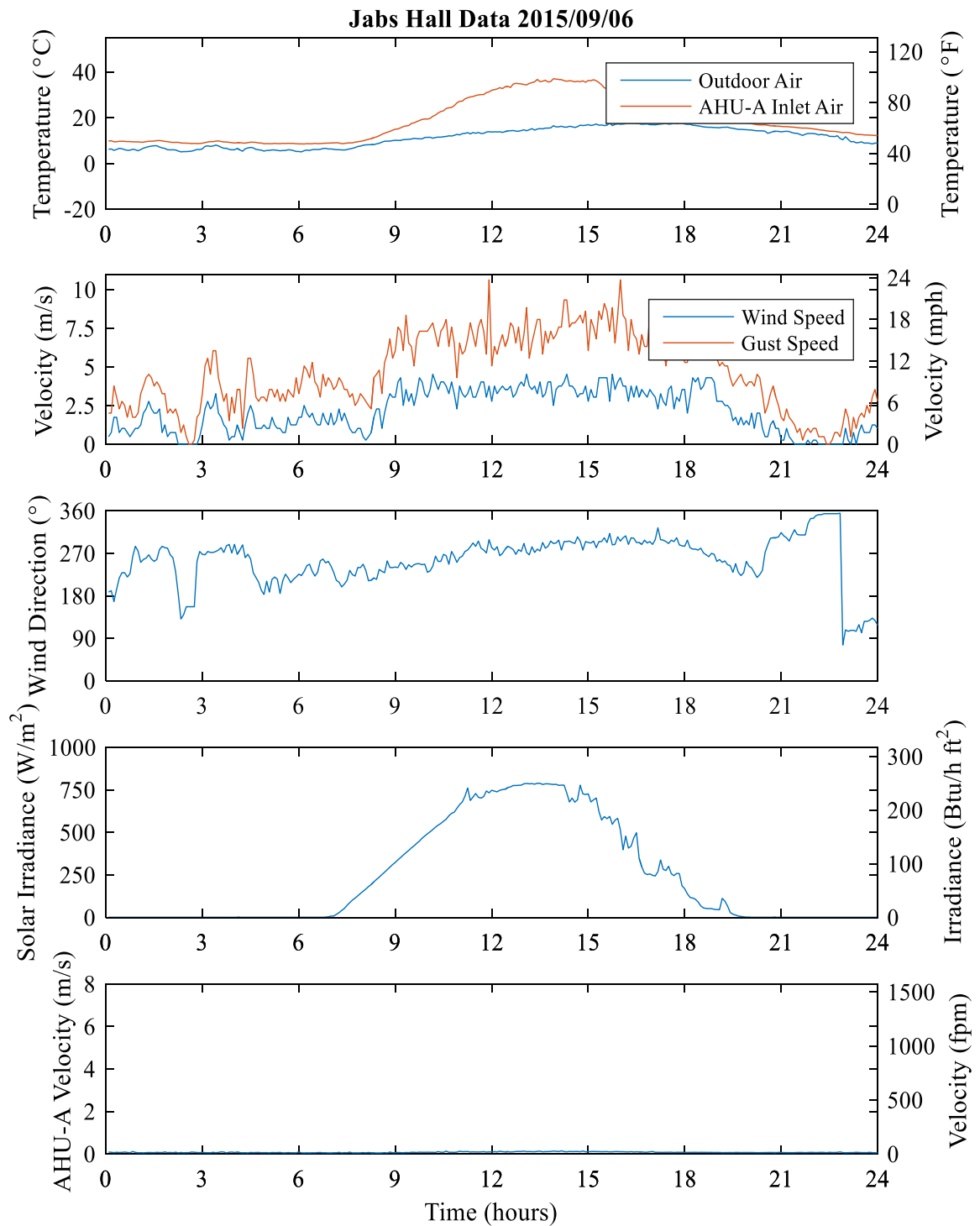


Figure 78: Jabs Hall Raw Data 2015/09/06

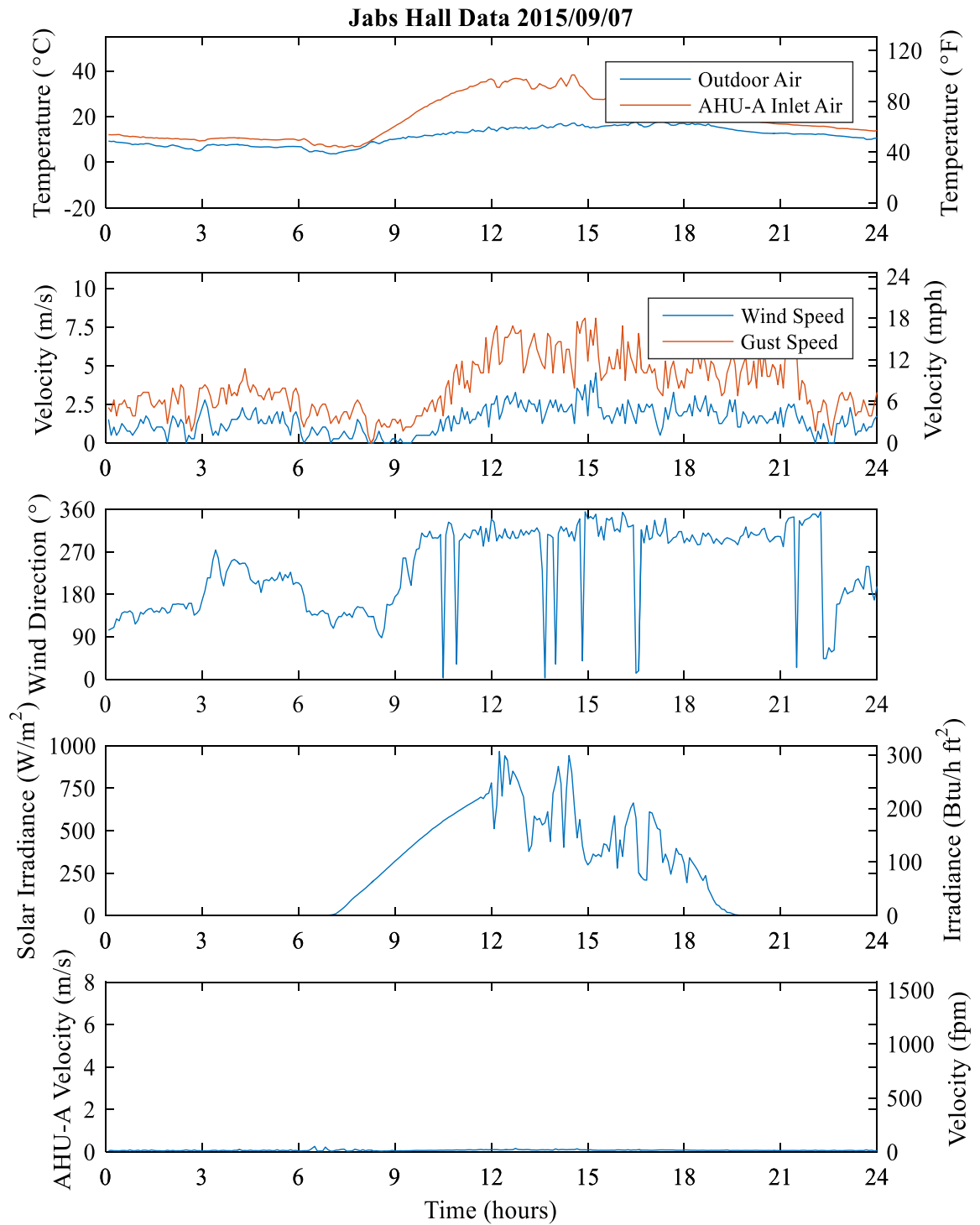


Figure 79: Jabs Hall Raw Data 2015/09/07

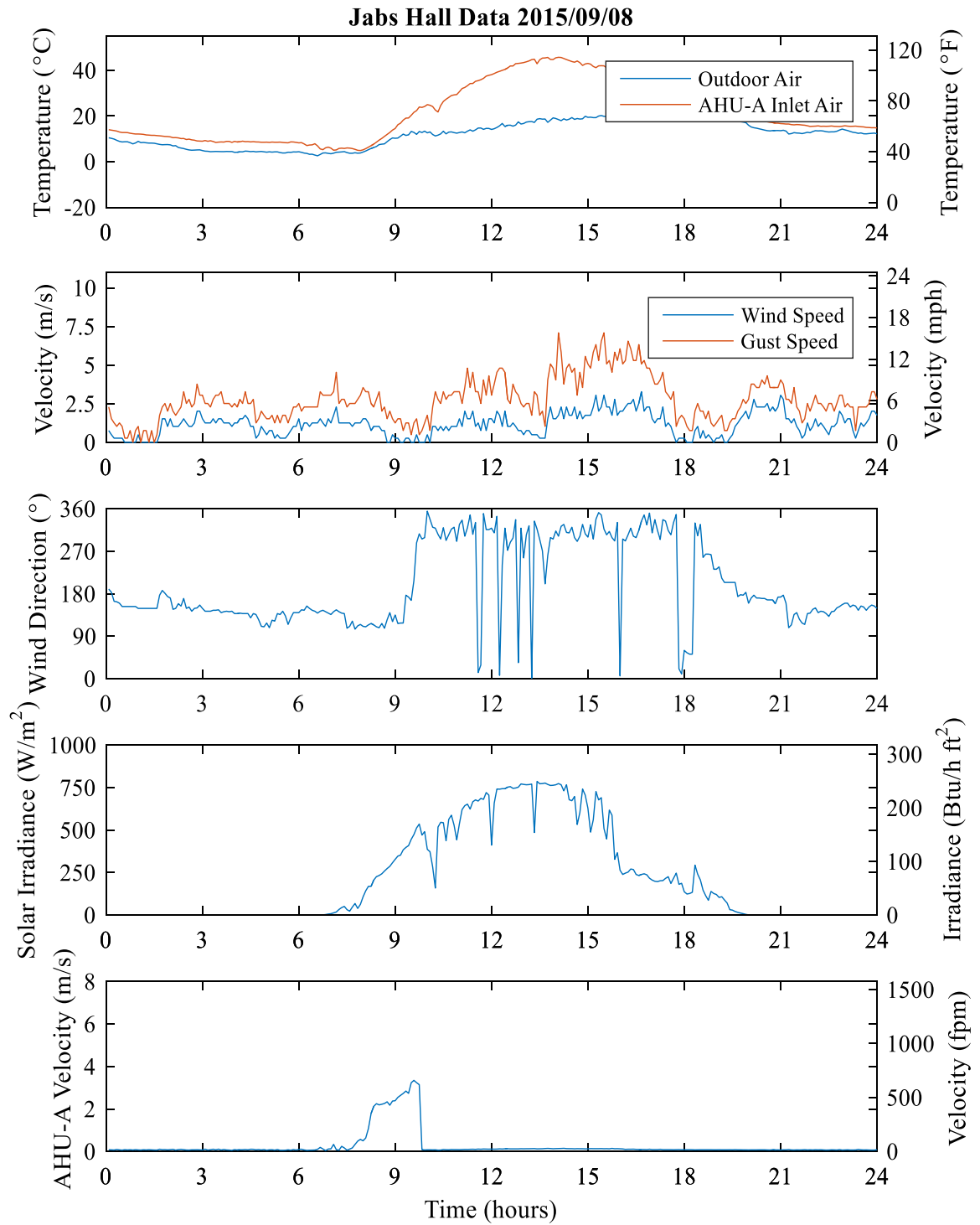


Figure 80: Jabs Hall Raw Data 2015/09/08

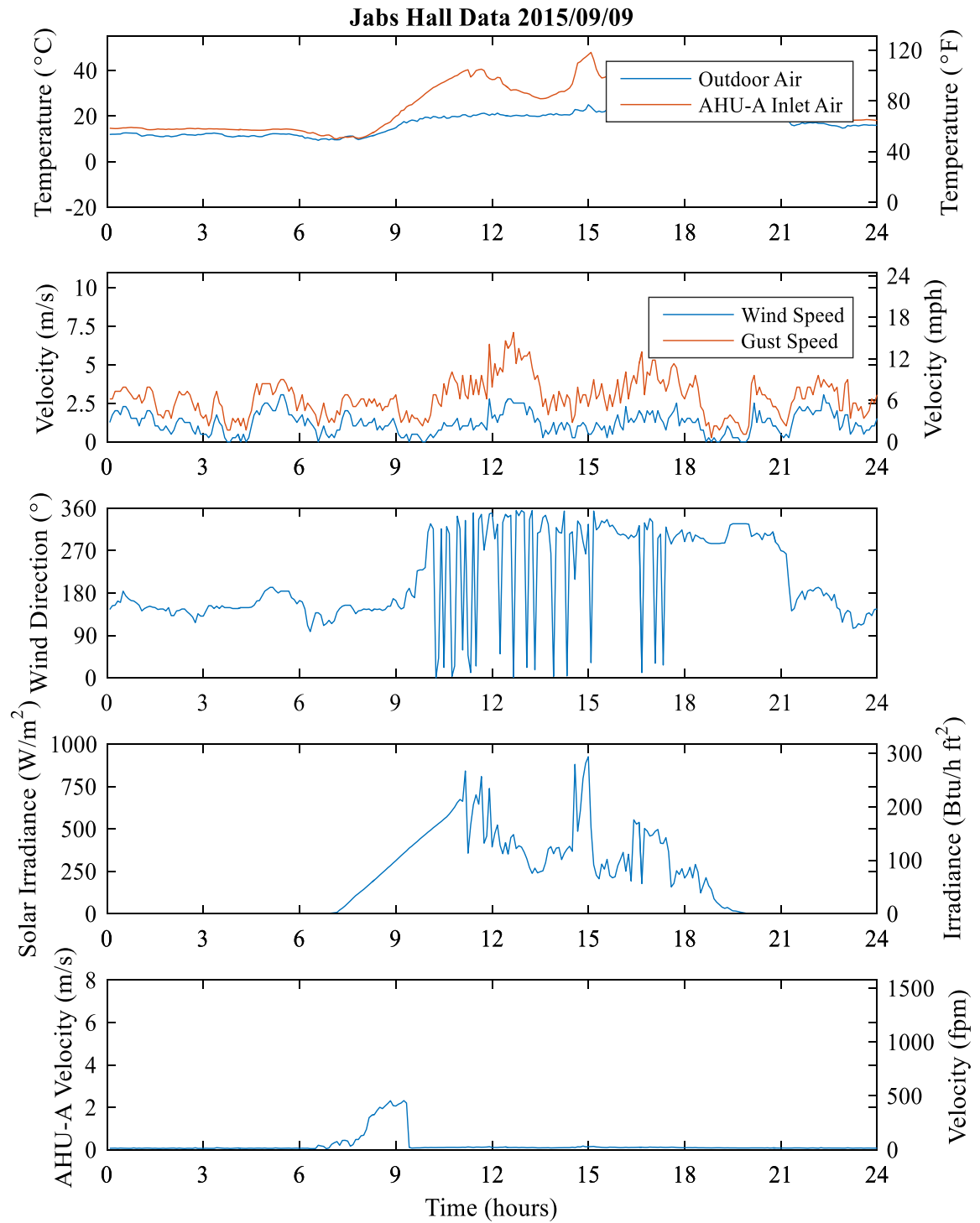


Figure 81: Jabs Hall Raw Data 2015/09/09

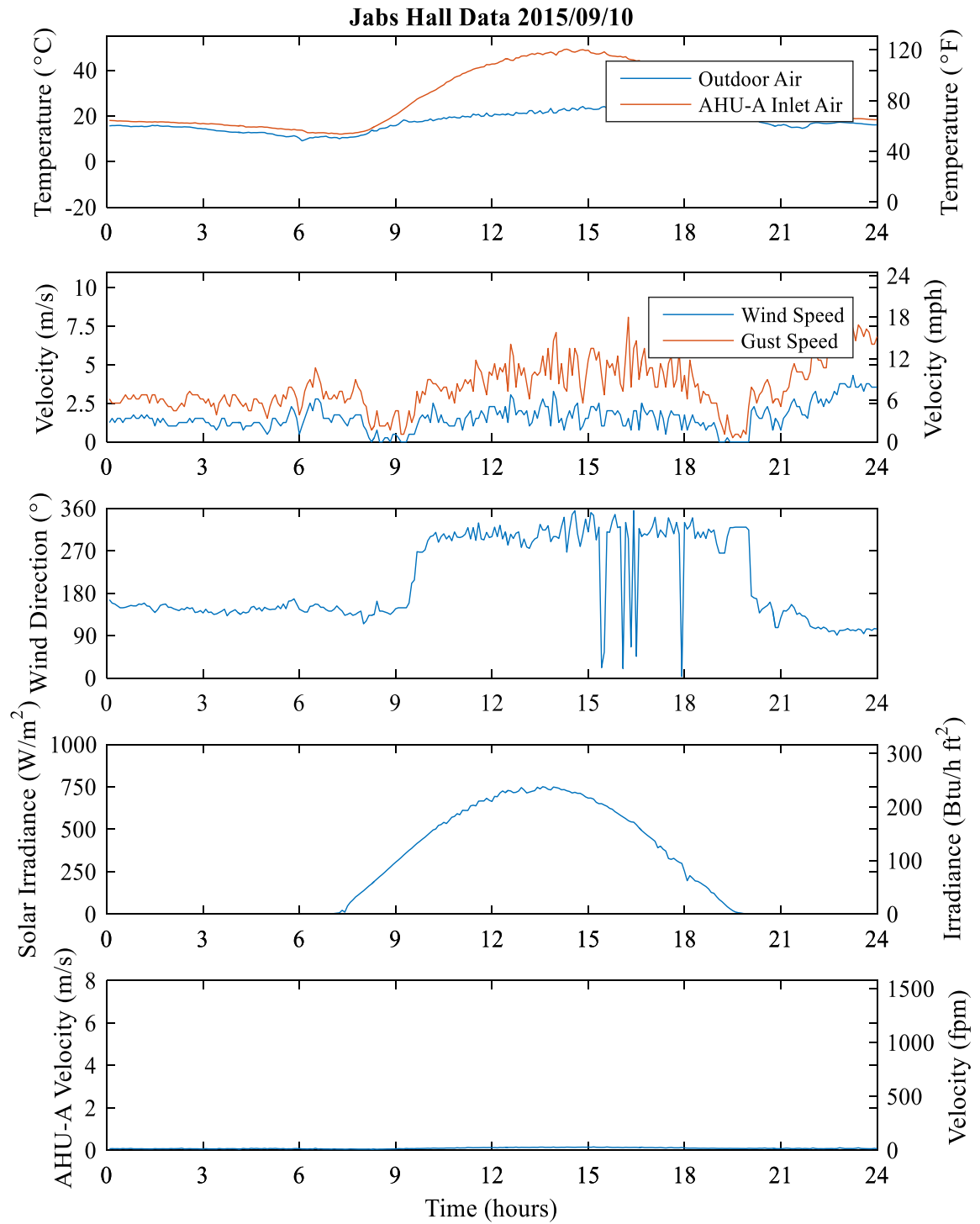


Figure 82: Jabs Hall Raw Data 2015/09/10

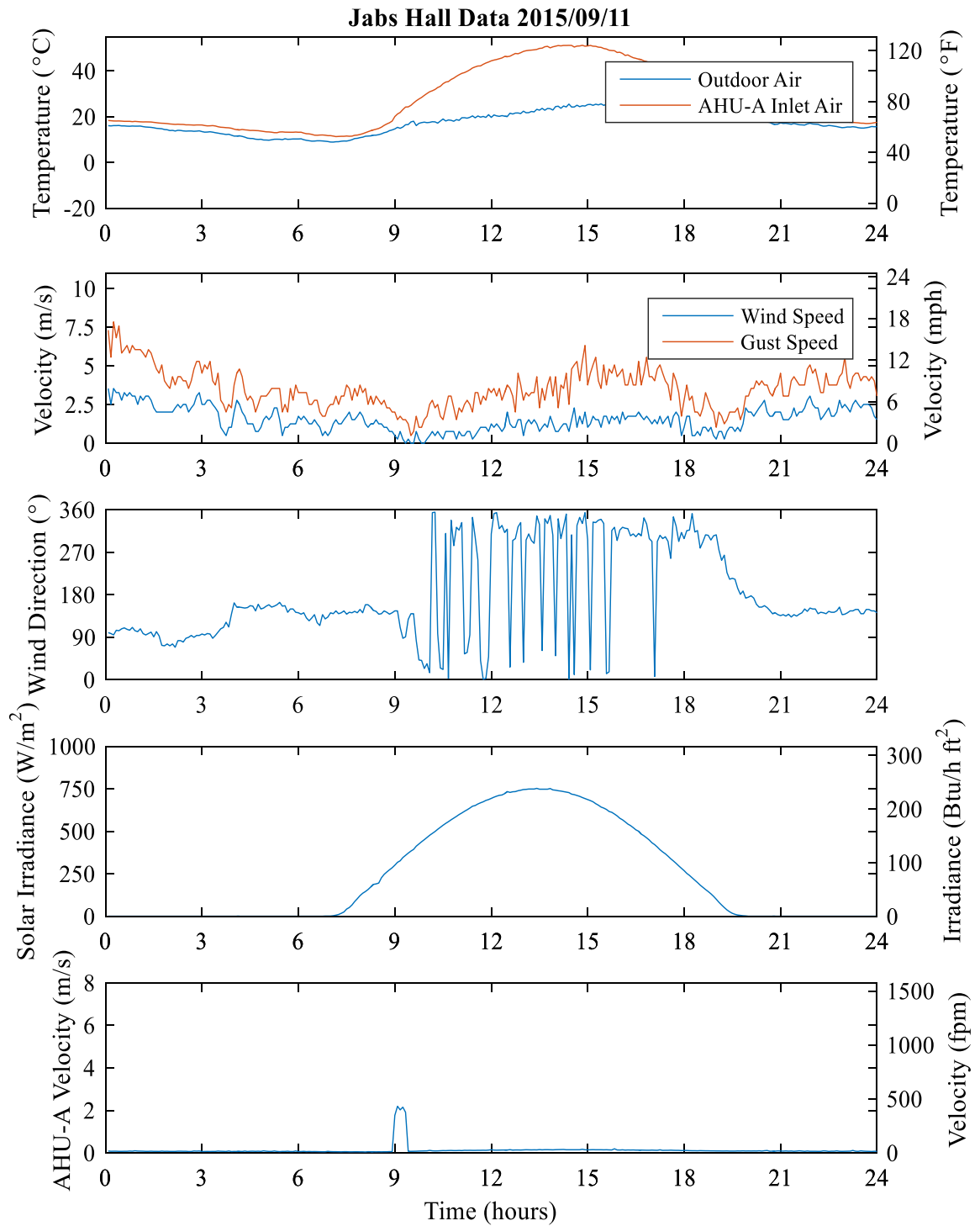


Figure 83: Jabs Hall Raw Data 2015/09/11

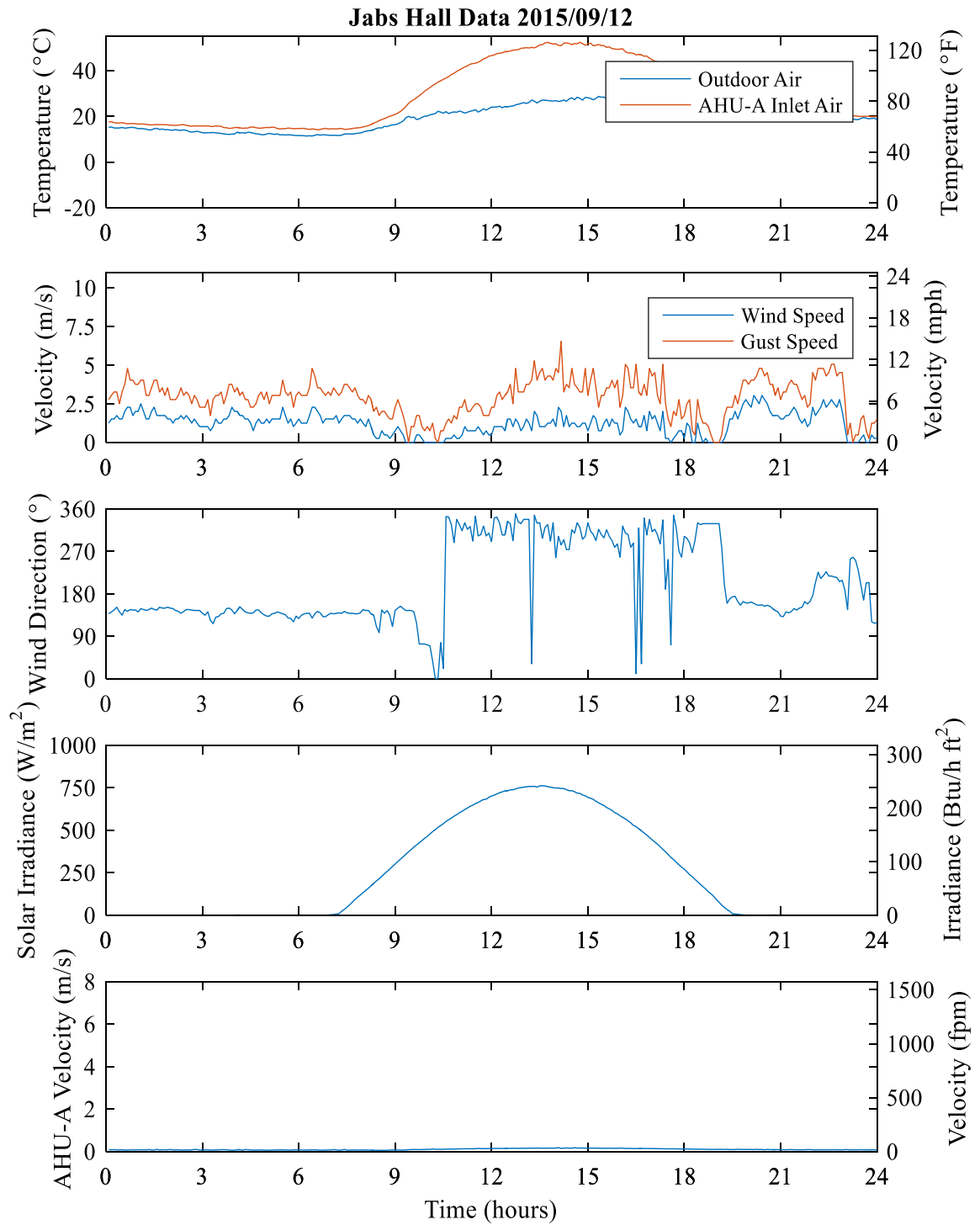


Figure 84: Jabs Hall Raw Data 2015/09/12

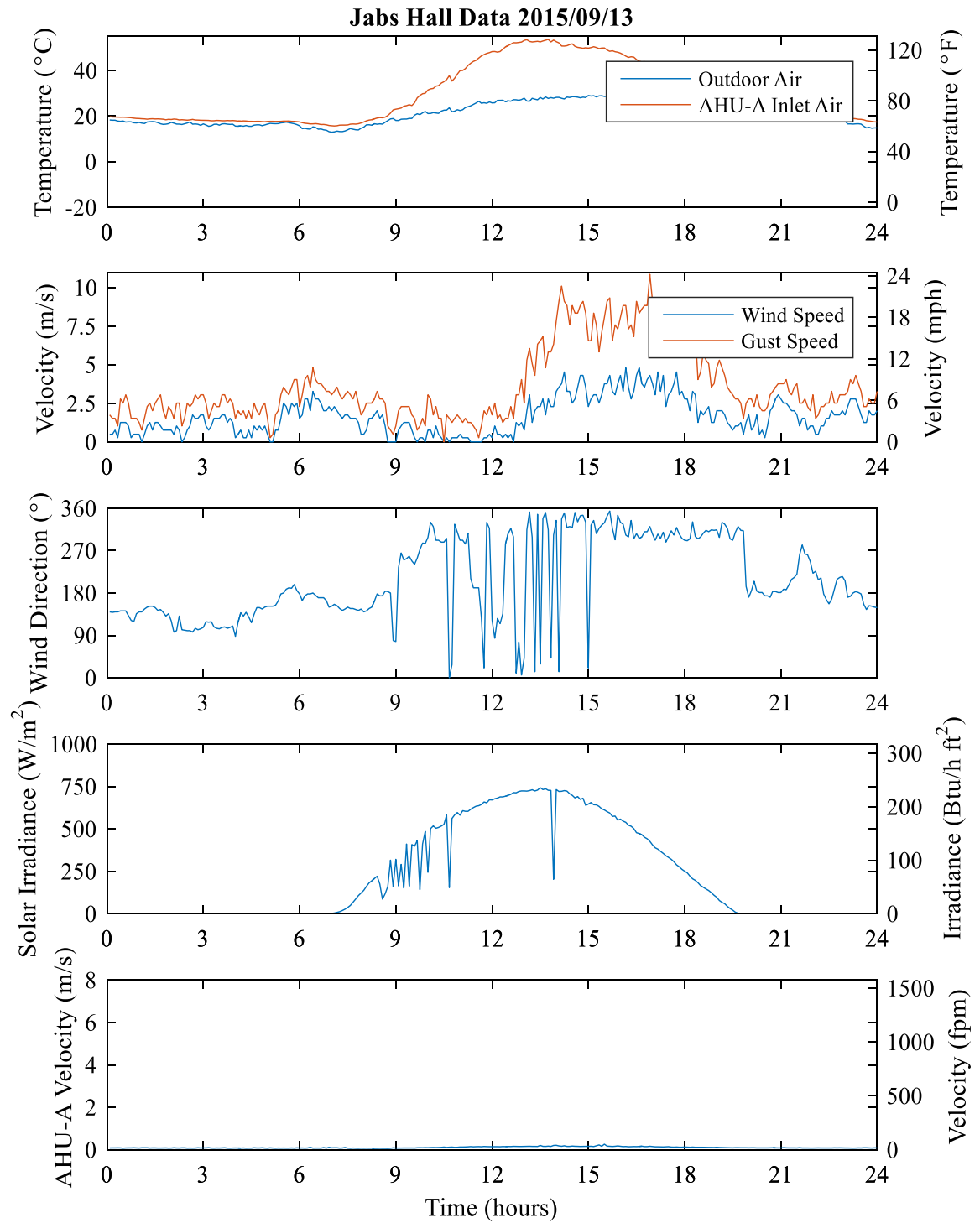


Figure 85: Jabs Hall Raw Data 2015/09/13

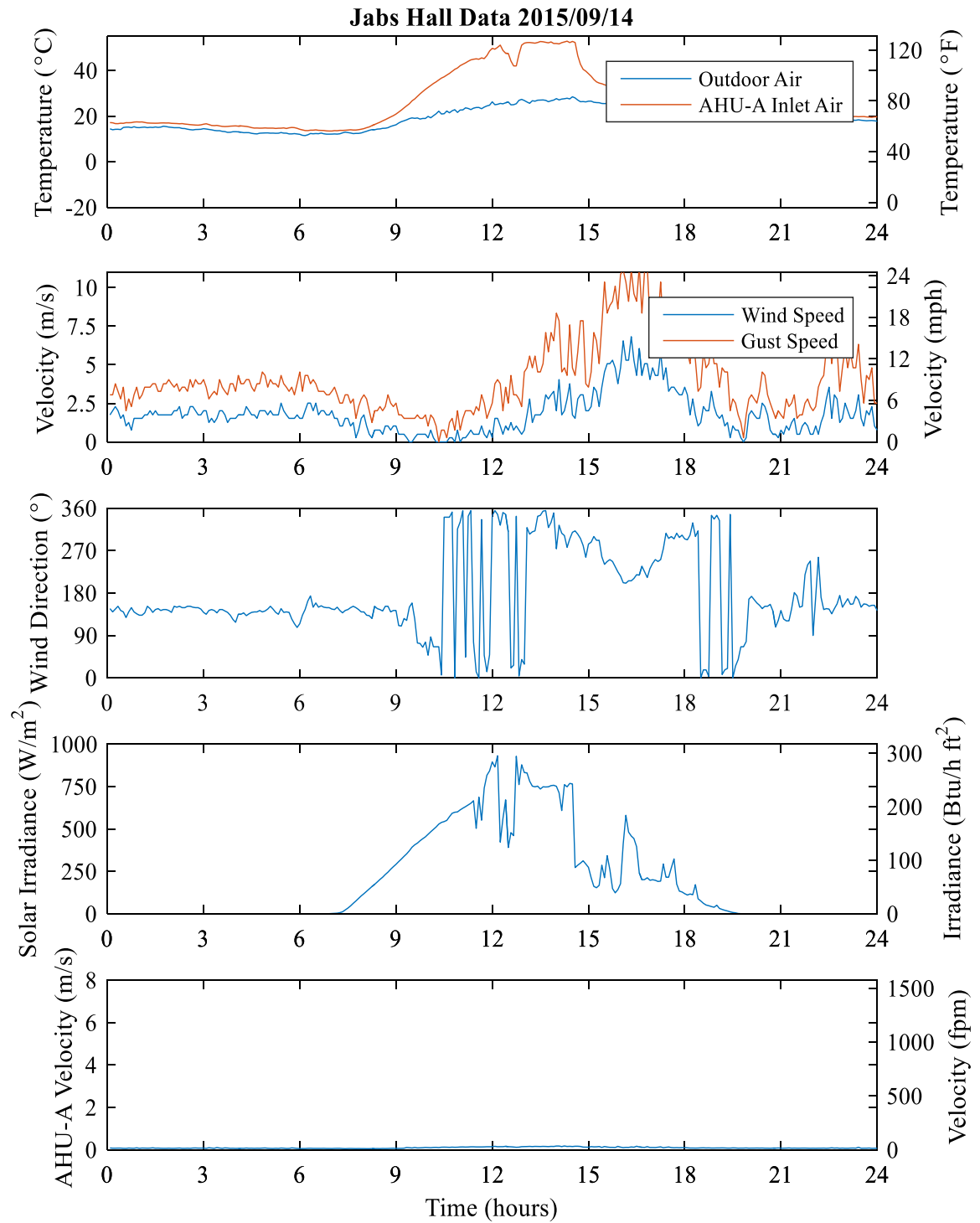


Figure 86: Jabs Hall Raw Data 2015/09/14

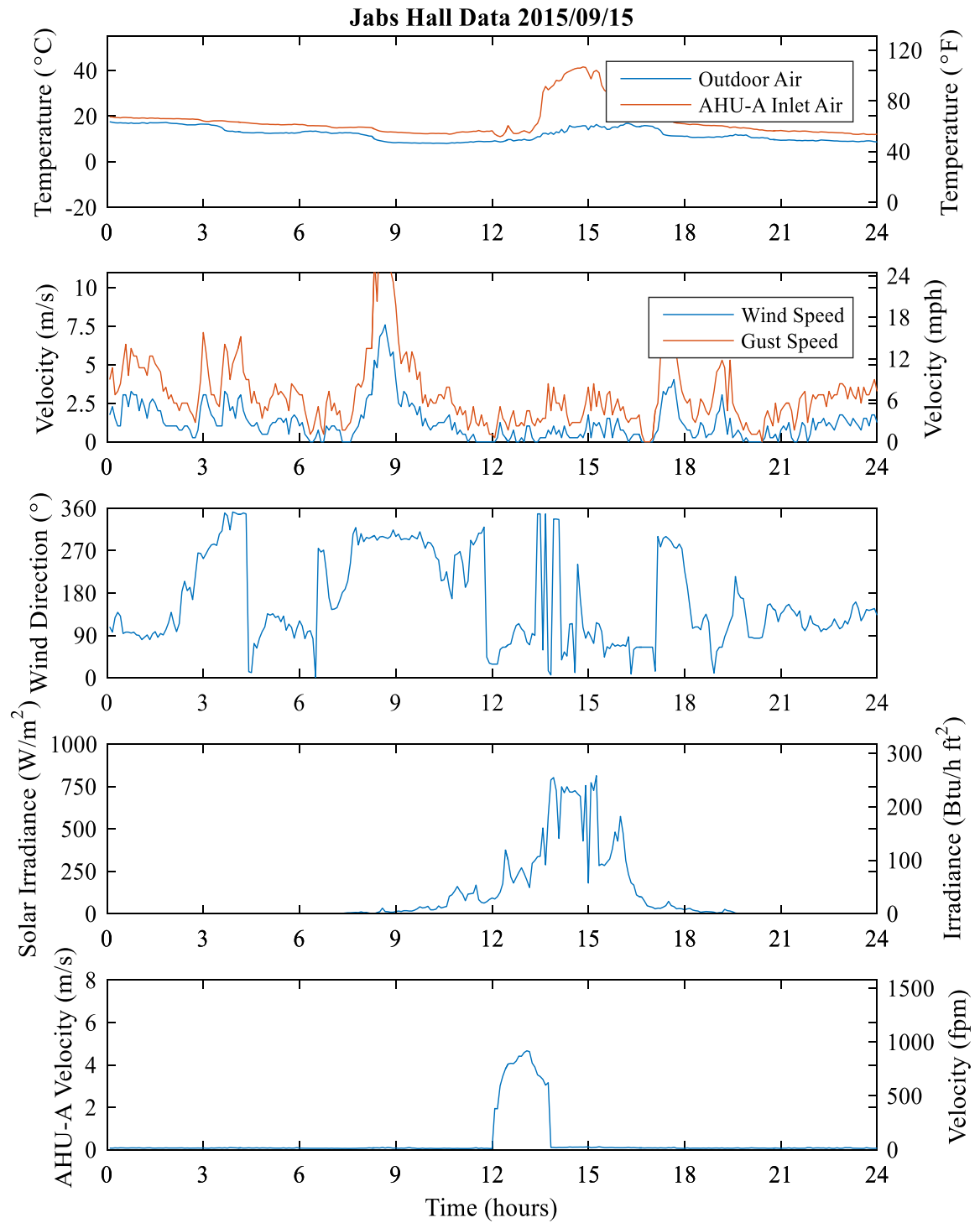


Figure 87: Jabs Hall Raw Data 2015/09/15

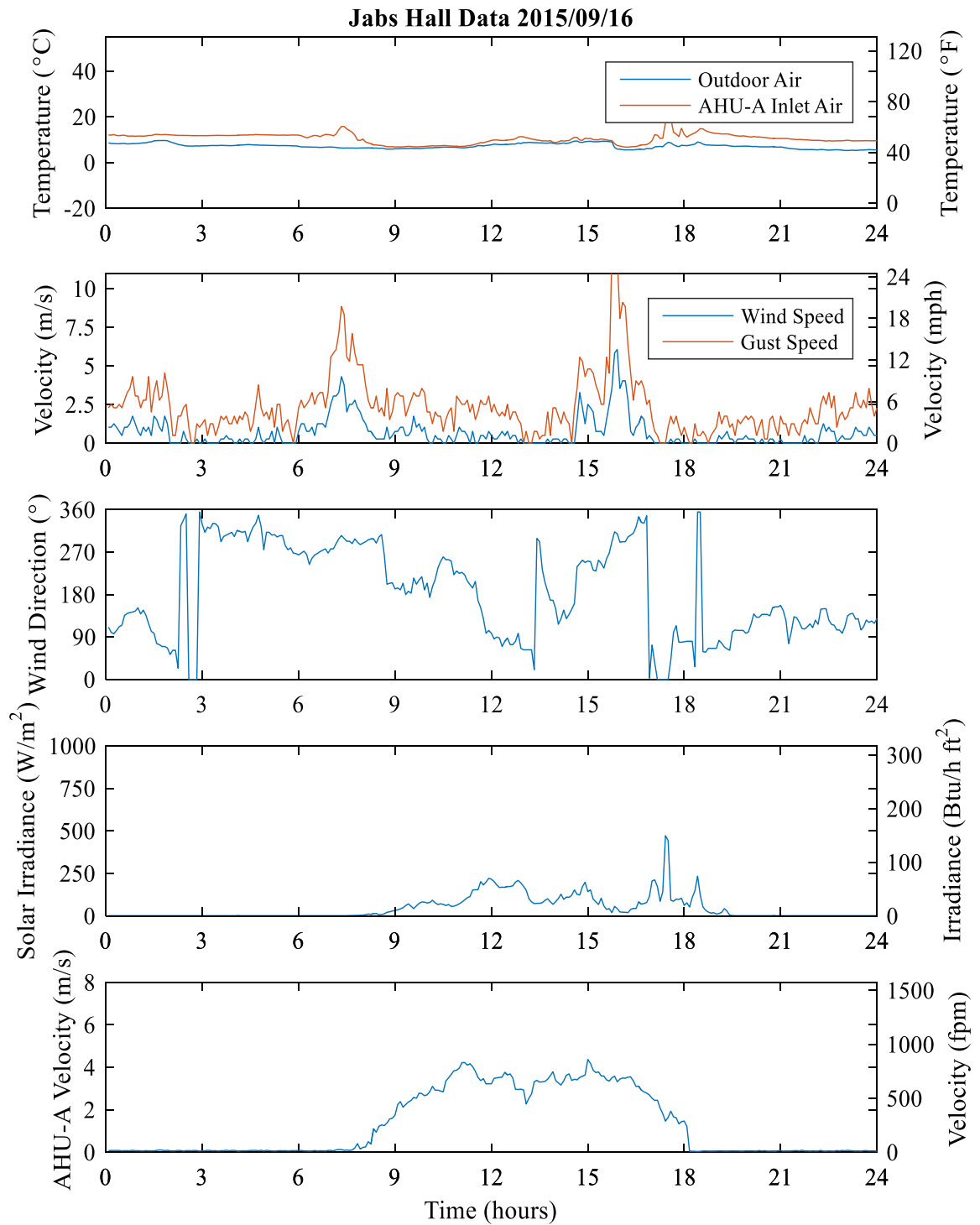


Figure 88: Jabs Hall Raw Data 2015/09/16

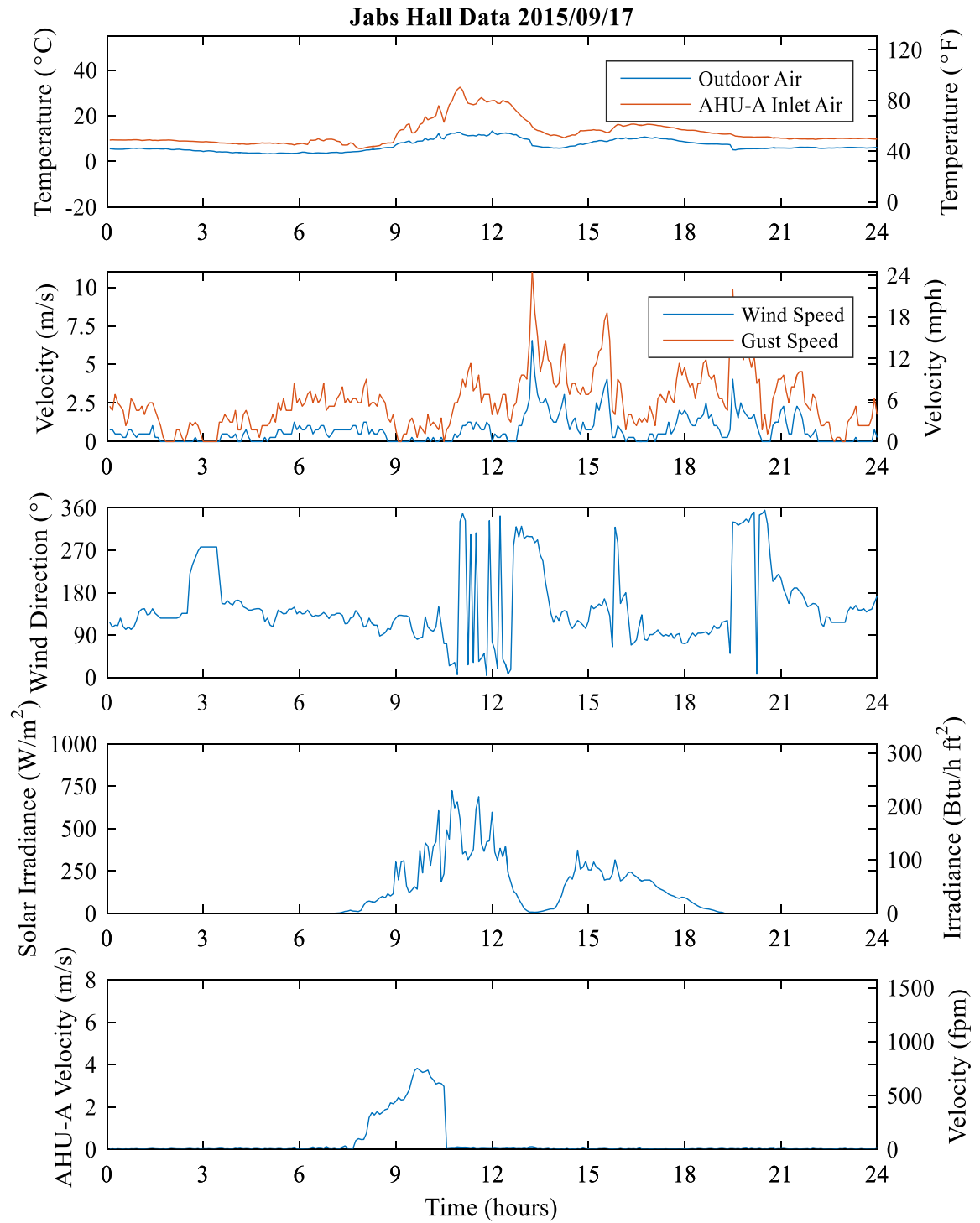


Figure 89: Jabs Hall Raw Data 2015/09/17

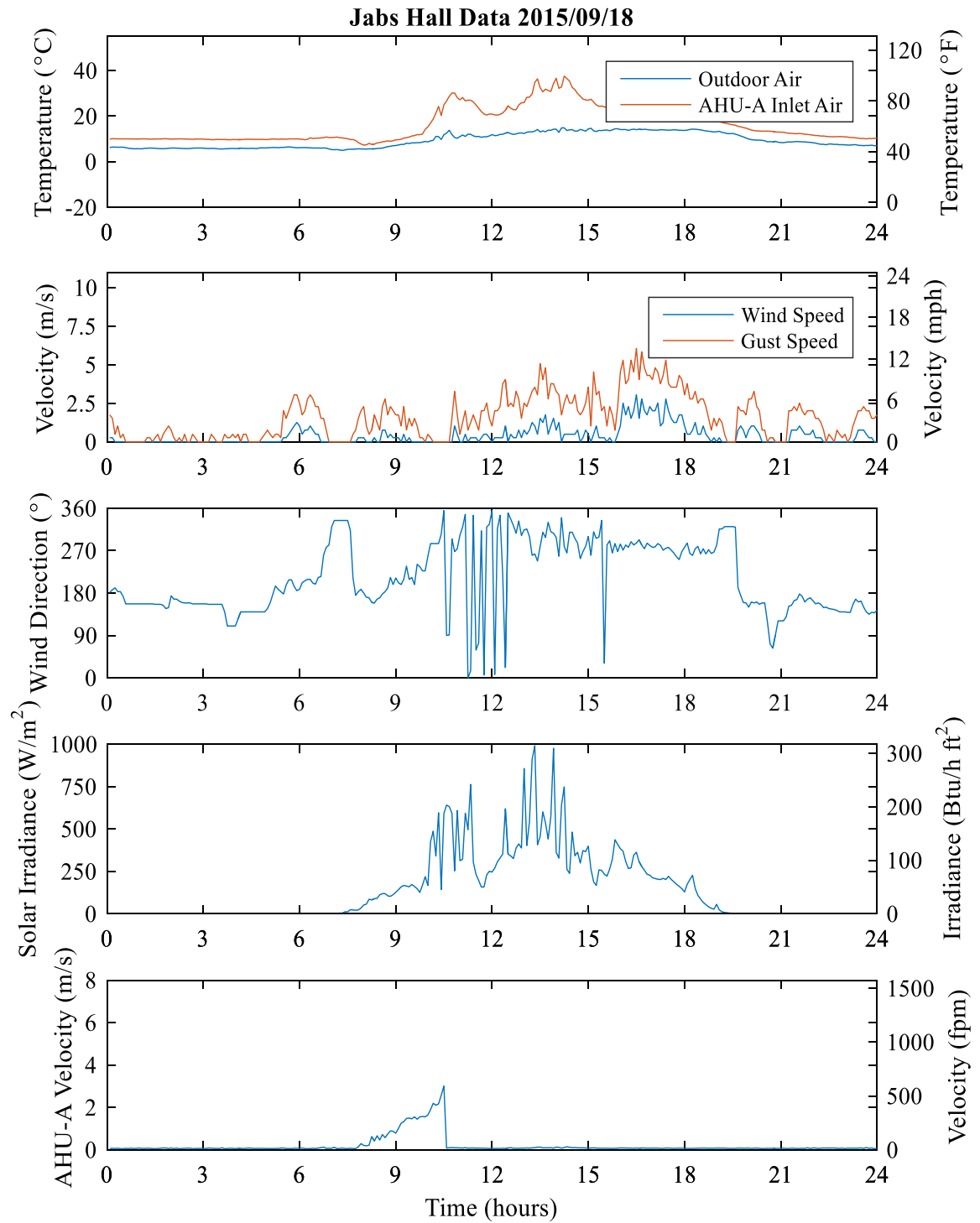


Figure 90: Jabs Hall Raw Data 2015/09/18

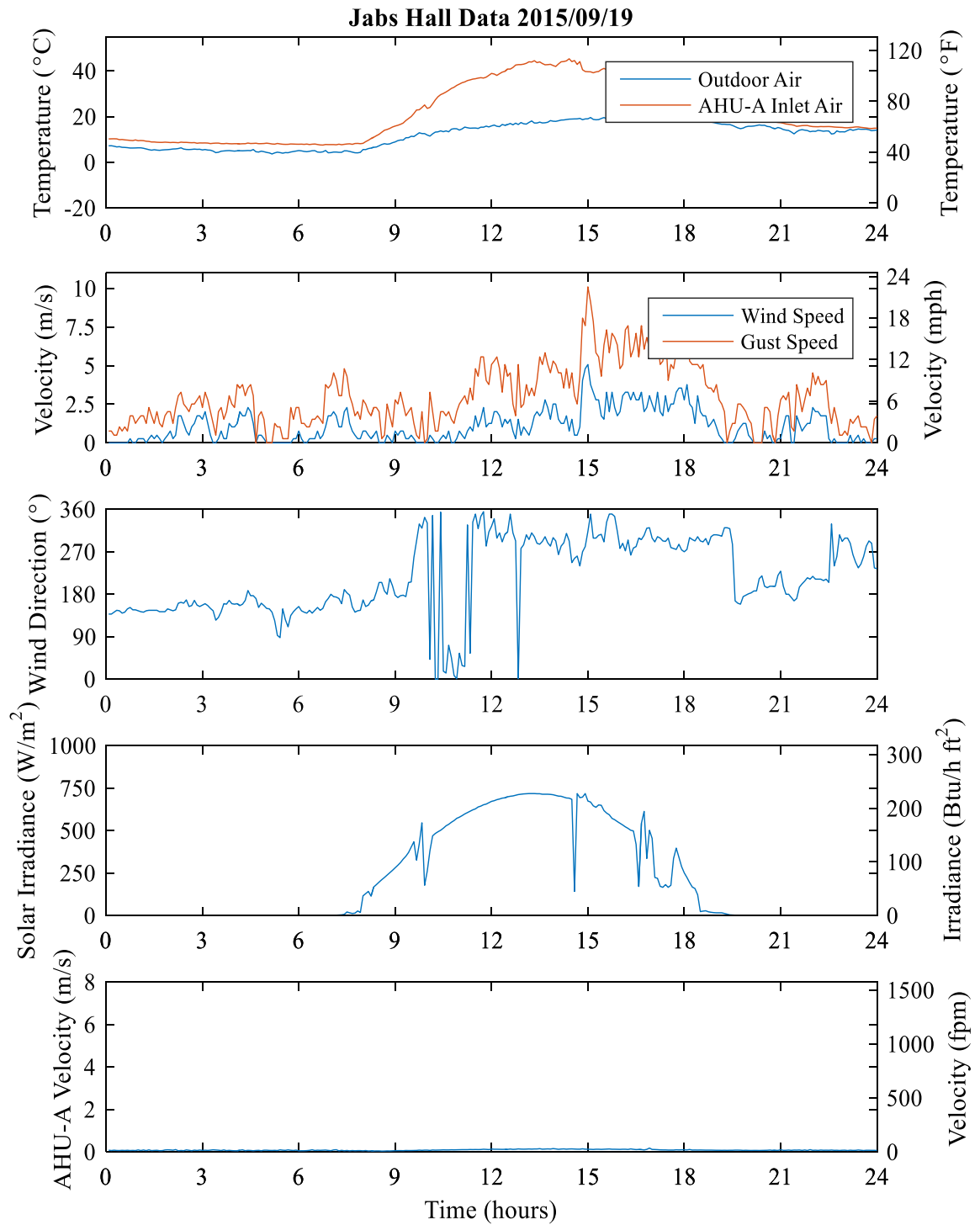


Figure 91: Jabs Hall Raw Data 2015/09/19

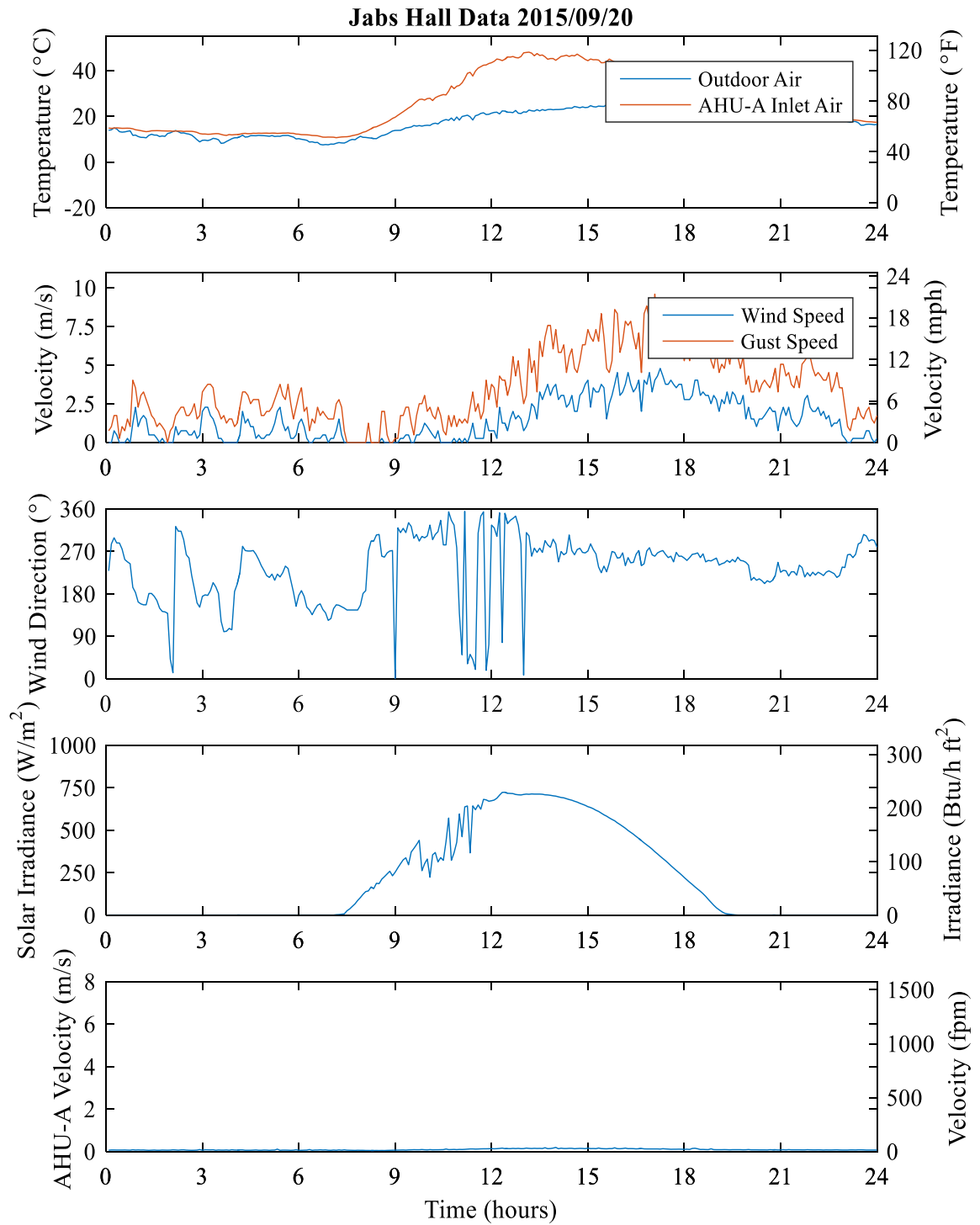


Figure 92: Jabs Hall Raw Data 2015/09/20

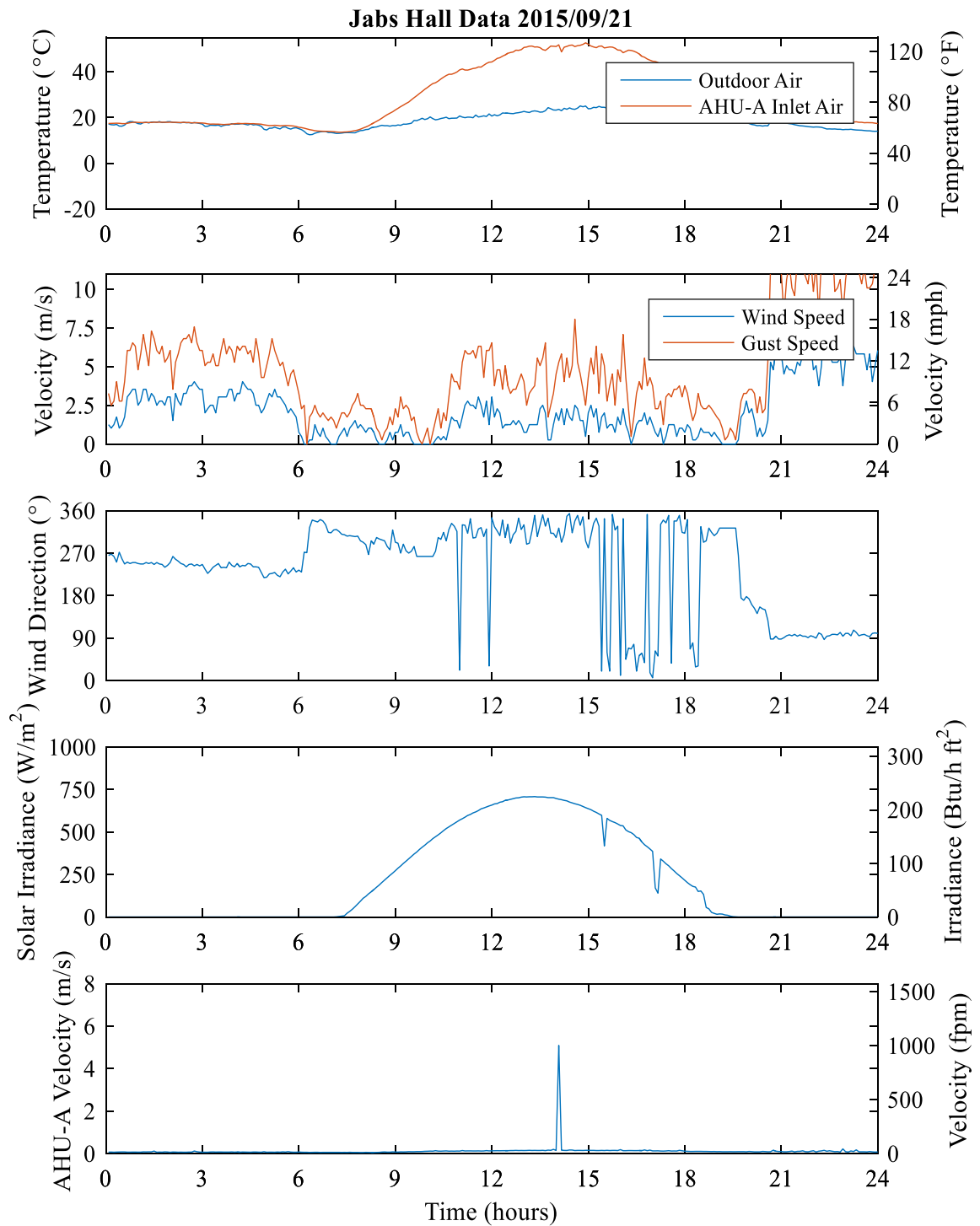


Figure 93: Jabs Hall Raw Data 2015/09/21

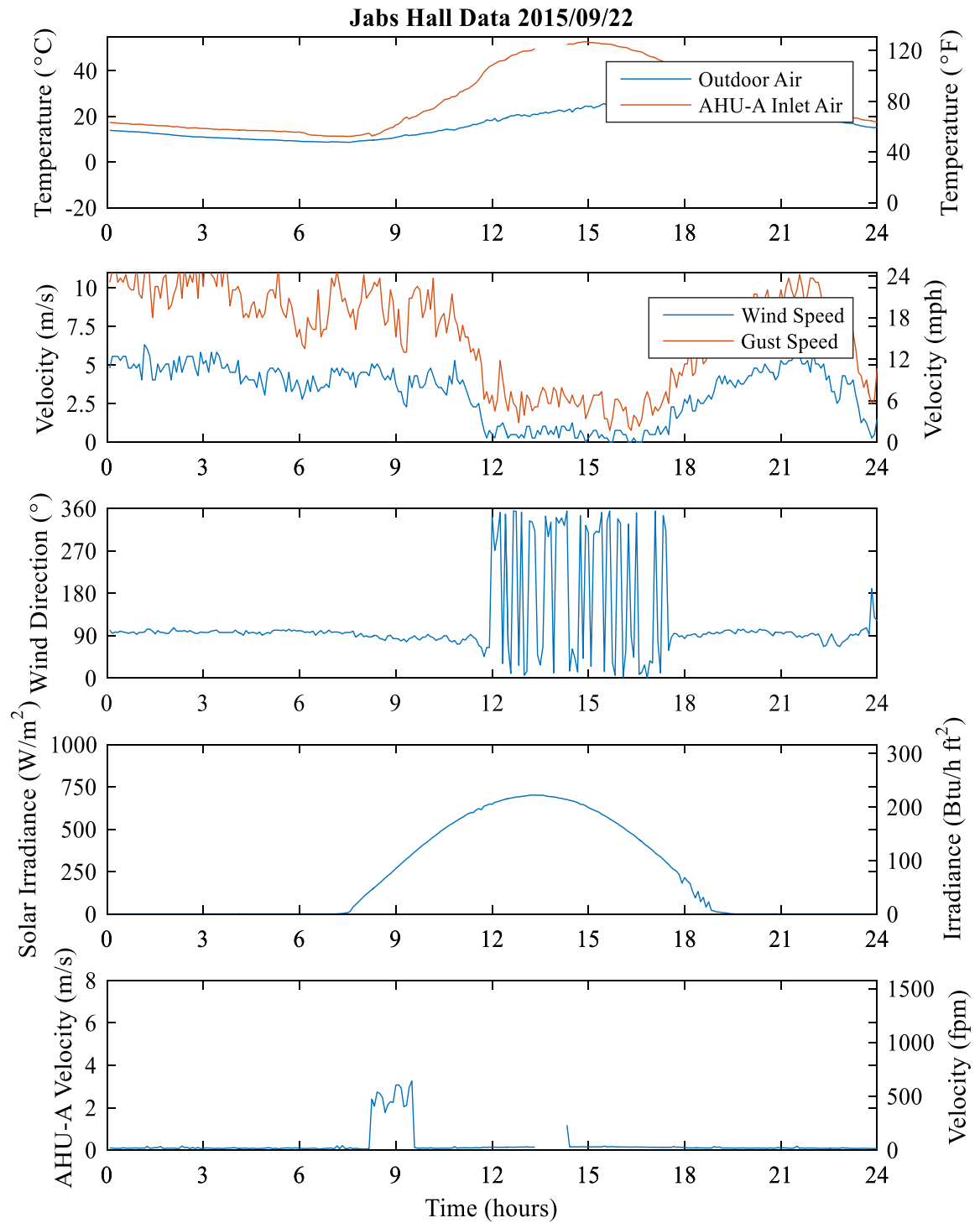


Figure 94: Jabs Hall Raw Data 2015/09/22

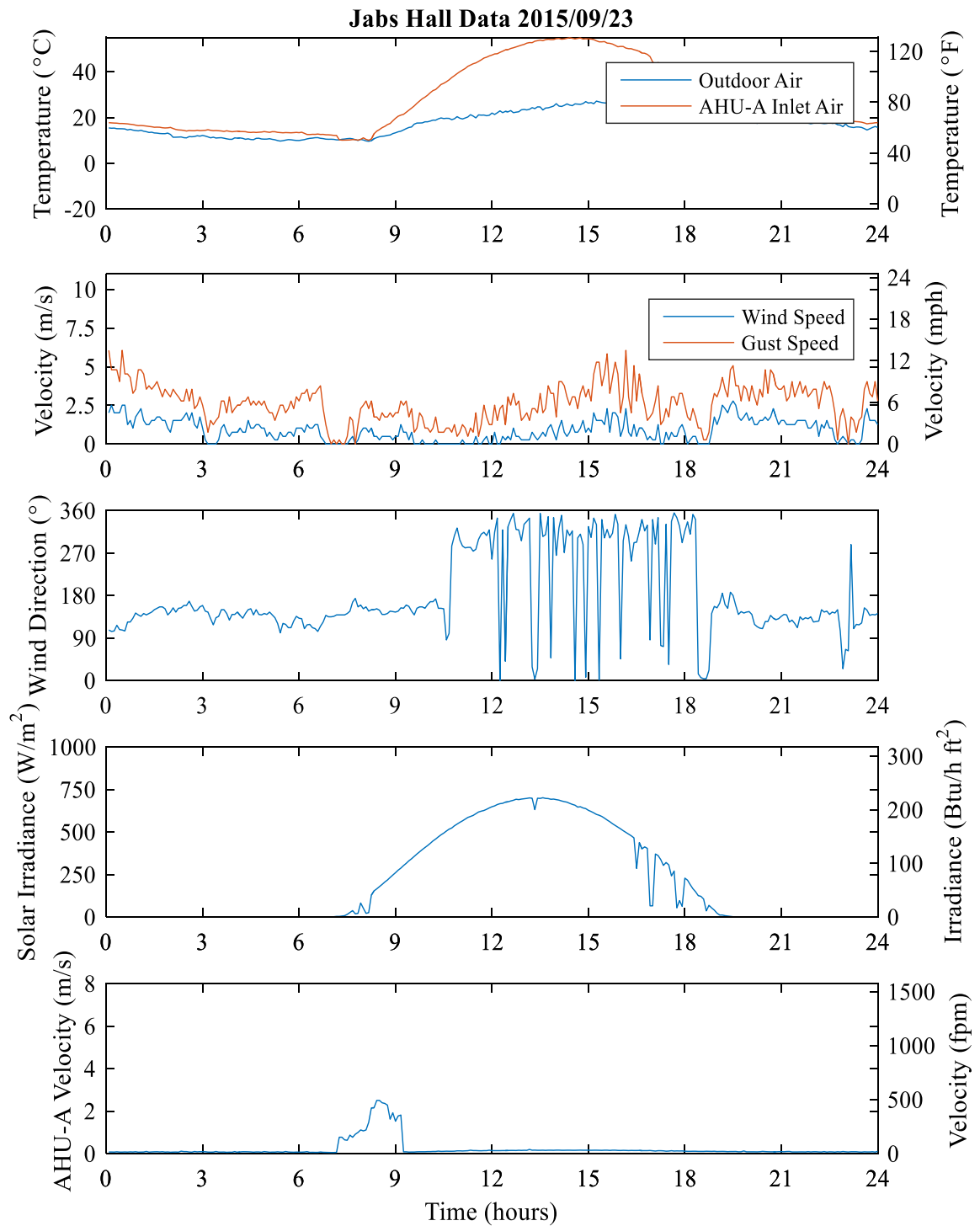


Figure 95: Jabs Hall Raw Data 2015/09/23

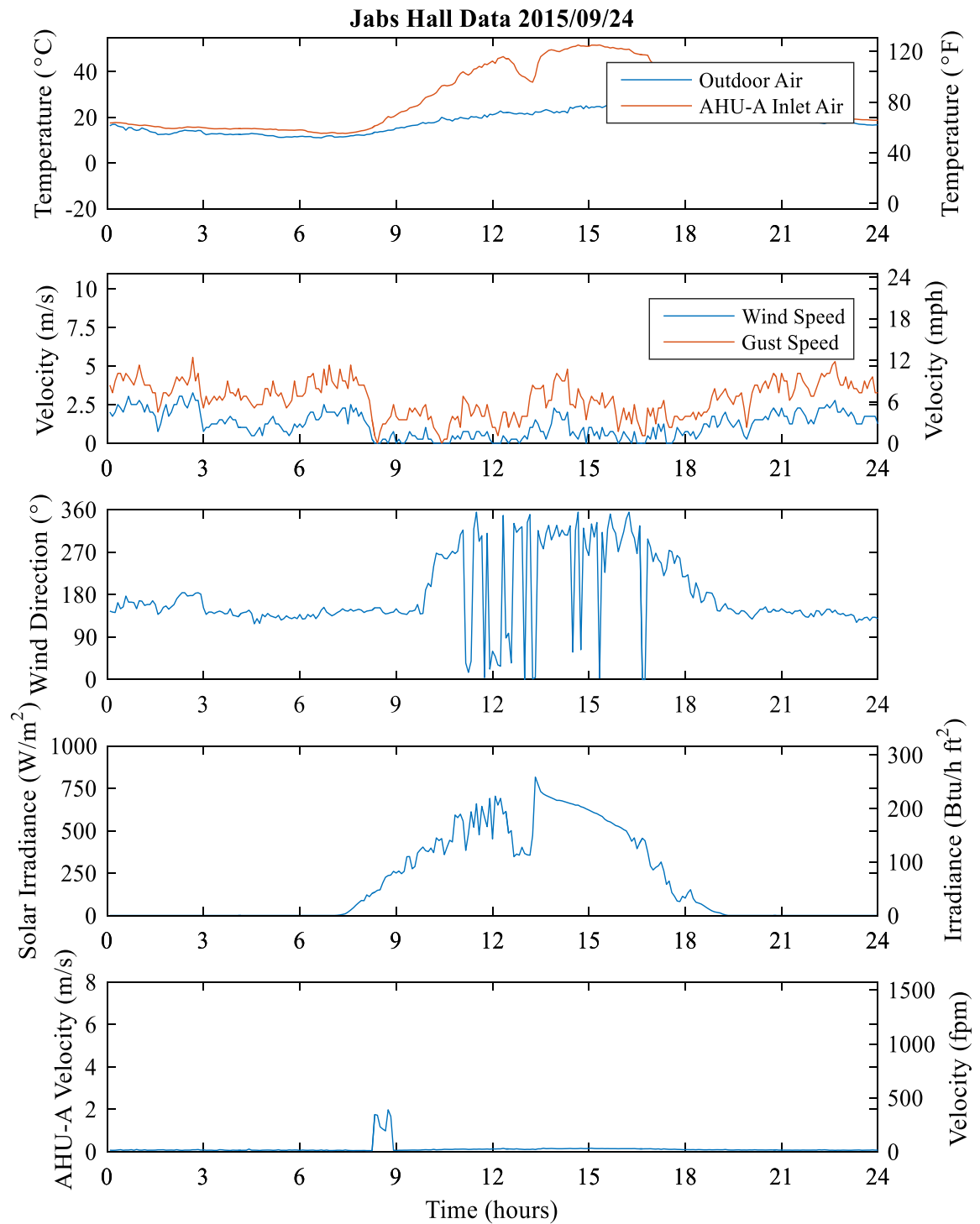


Figure 96: Jabs Hall Raw Data 2015/09/24

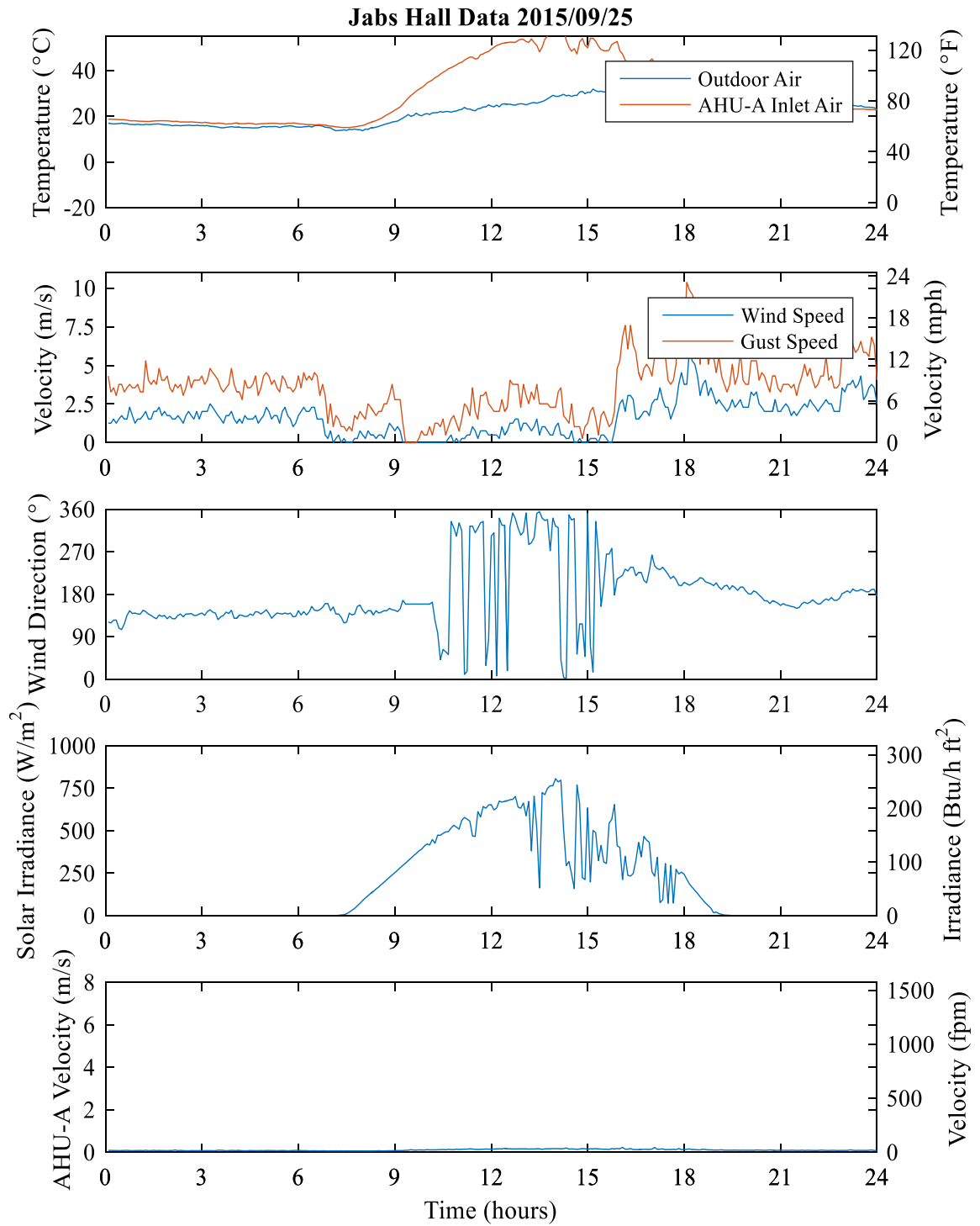


Figure 97: Jabs Hall Raw Data 2015/09/25

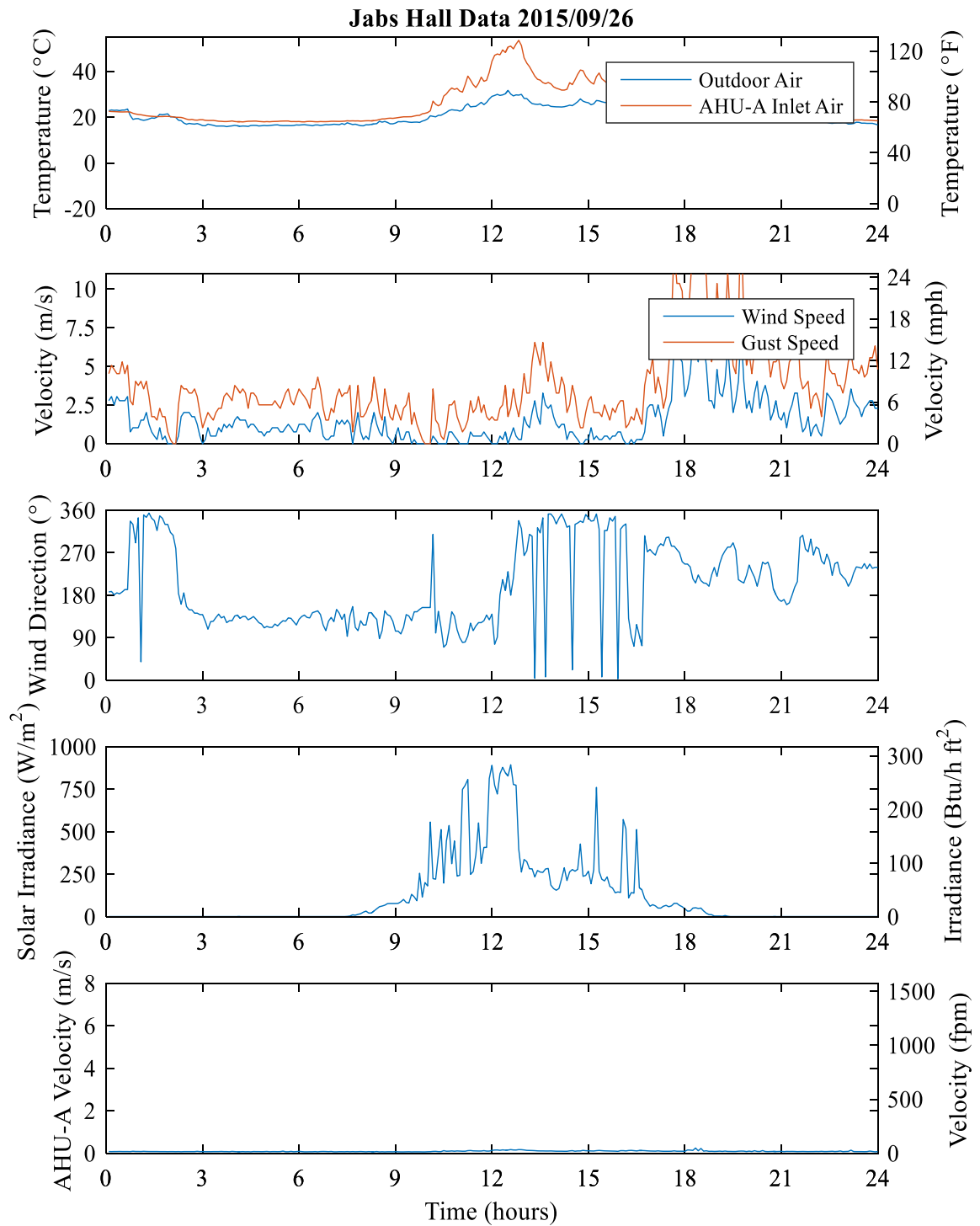


Figure 98: Jabs Hall Raw Data 2015/09/26

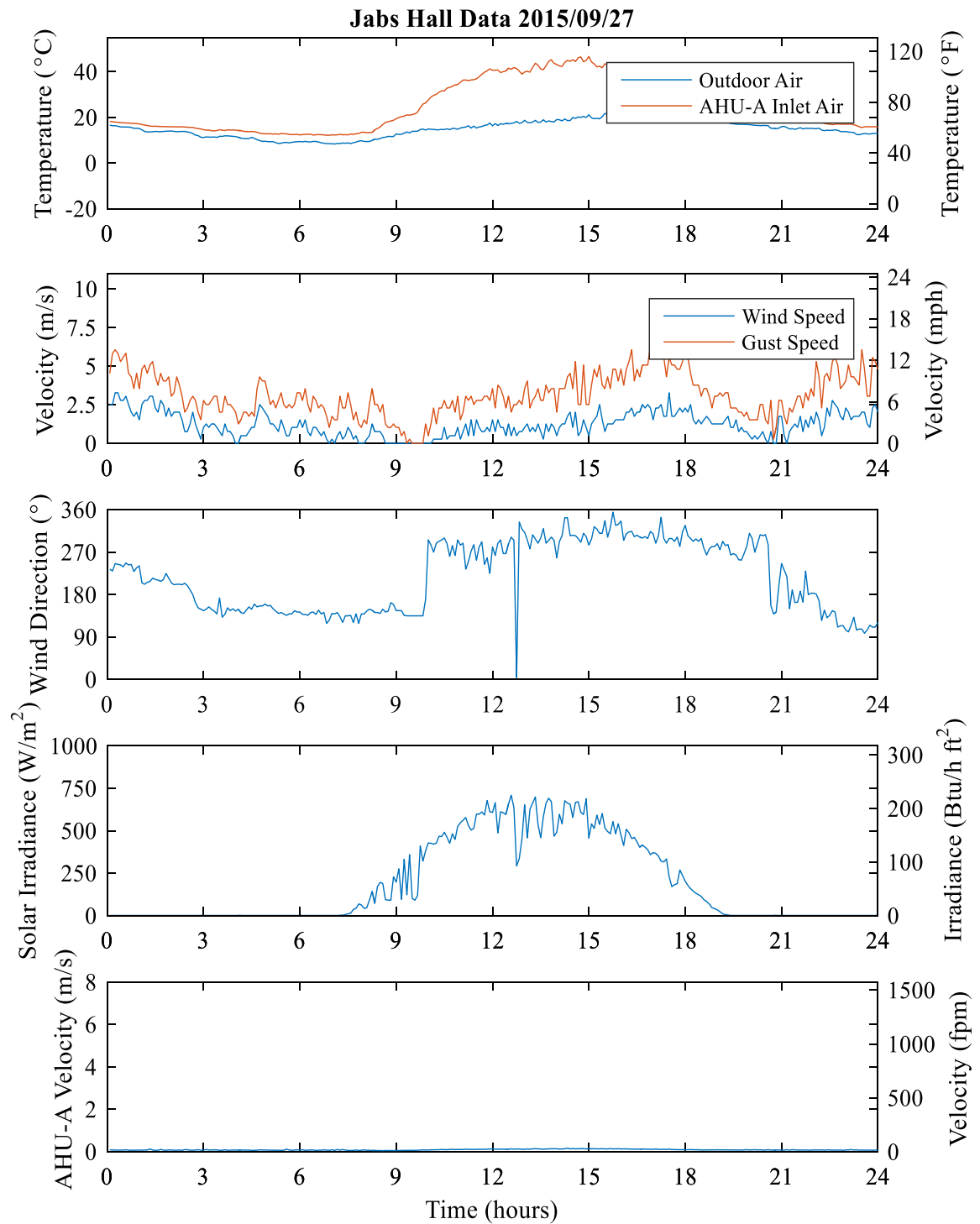


Figure 99: Jabs Hall Raw Data 2015/09/27

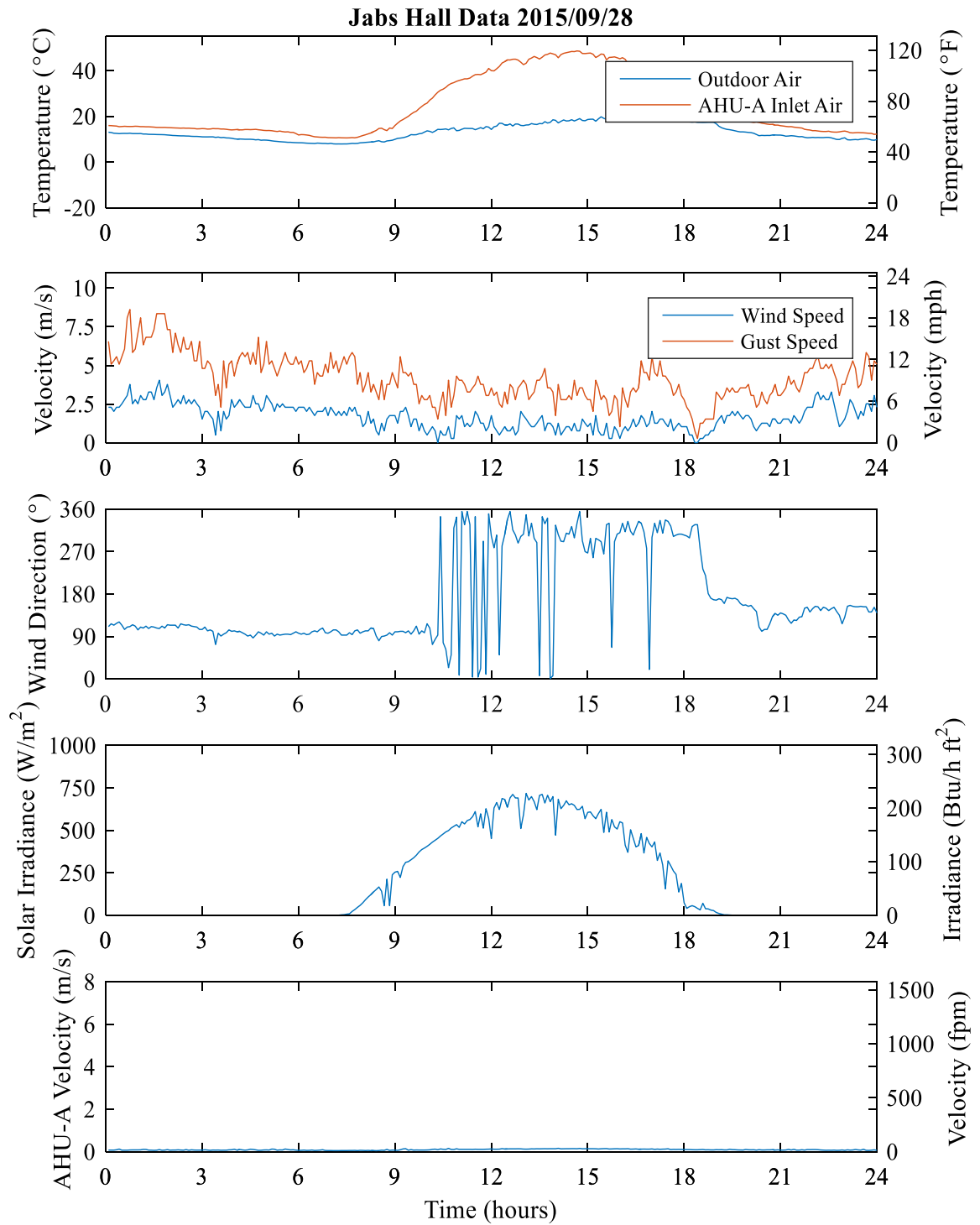


Figure 100: Jabs Hall Raw Data 2015/09/28

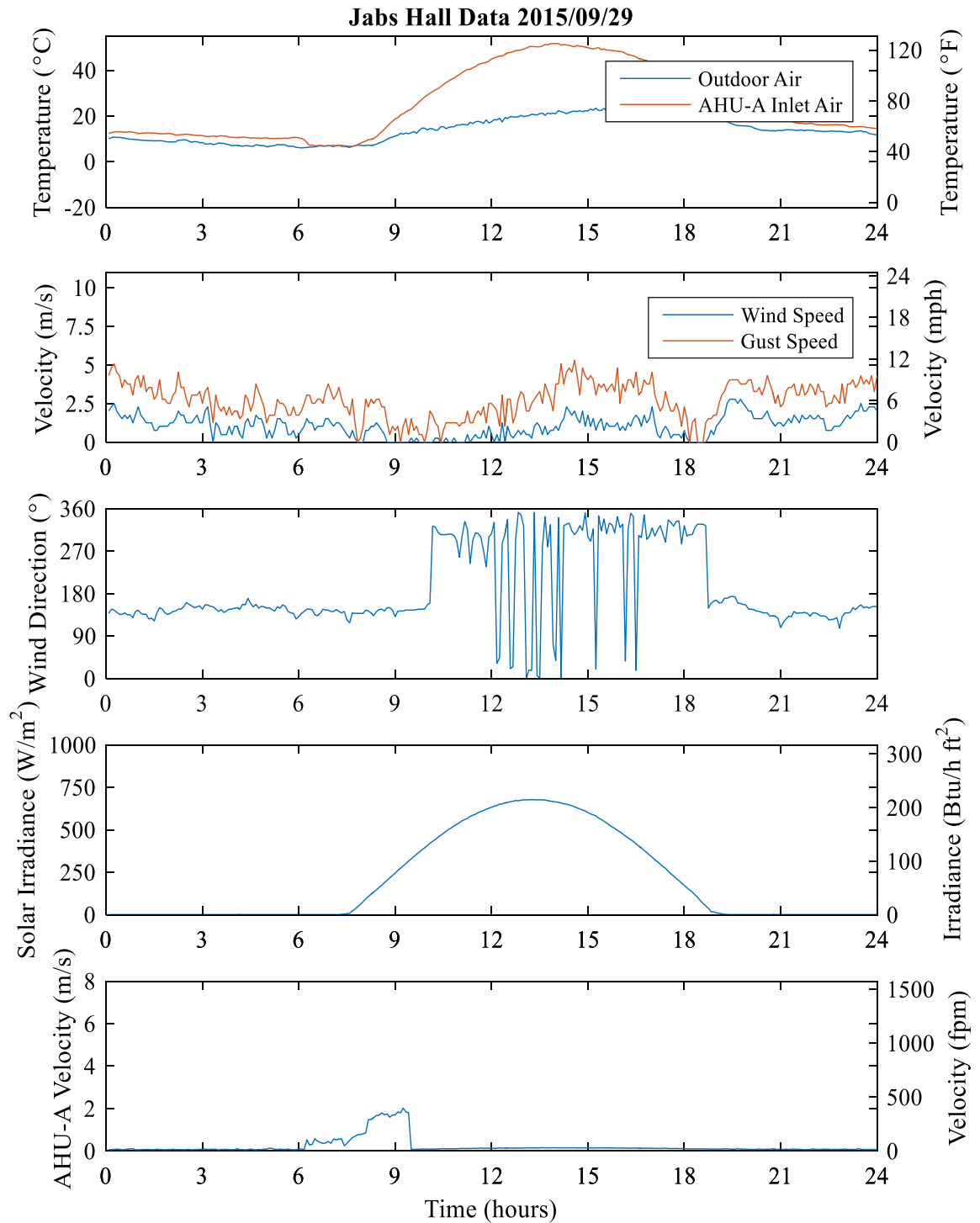


Figure 101: Jabs Hall Raw Data 2015/09/29

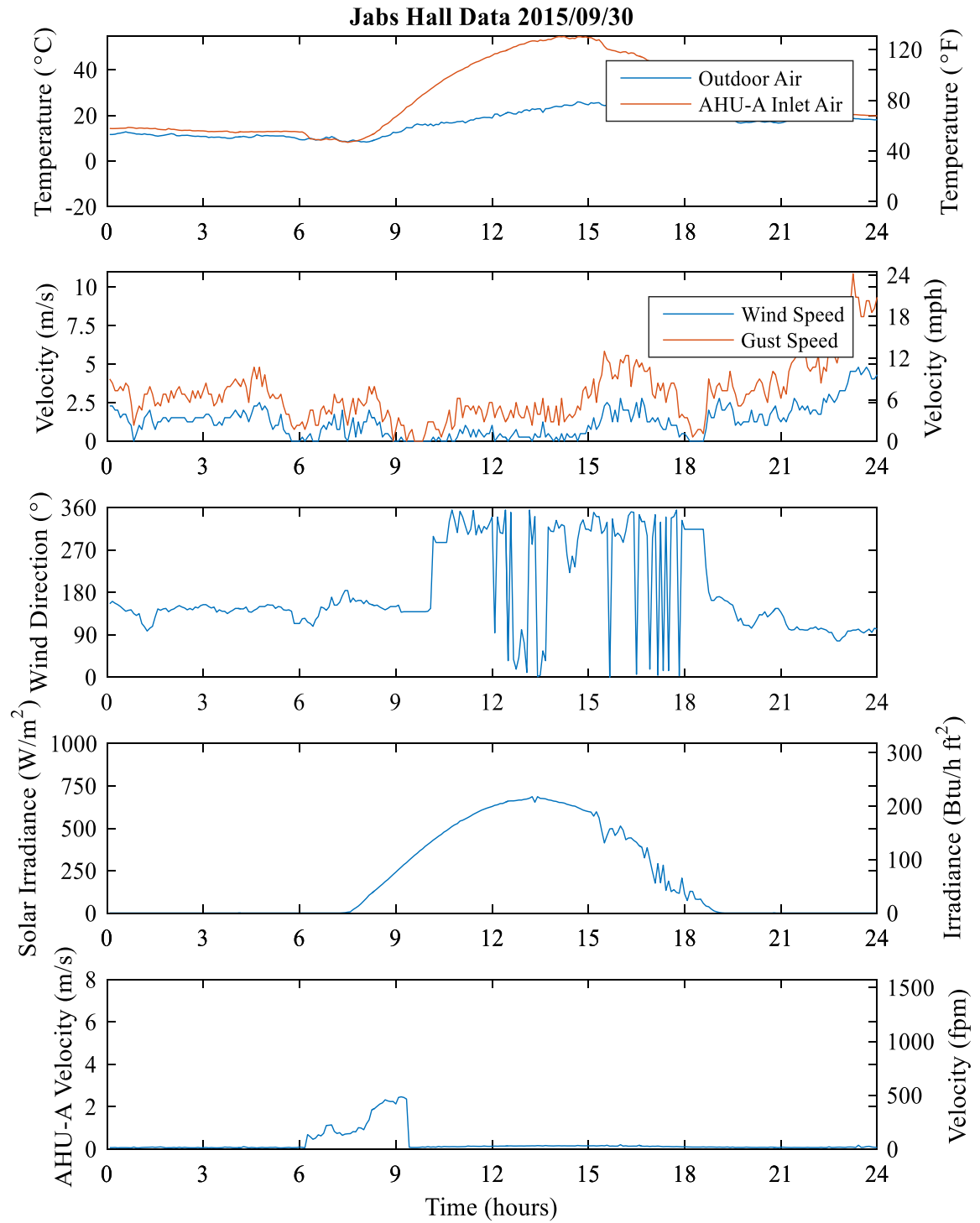


Figure 102: Jabs Hall Raw Data 2015/09/30

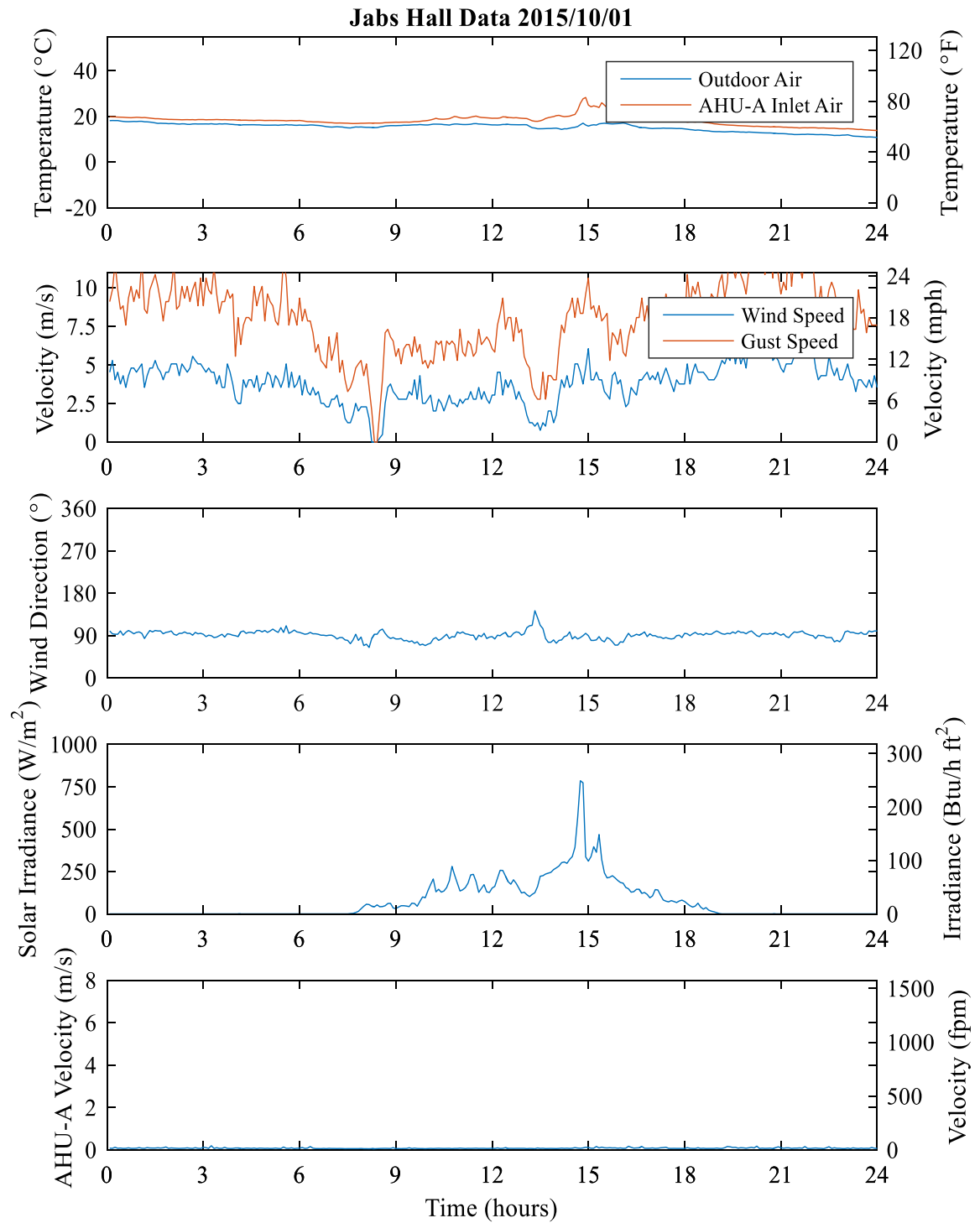


Figure 103: Jabs Hall Raw Data 2015/10/01

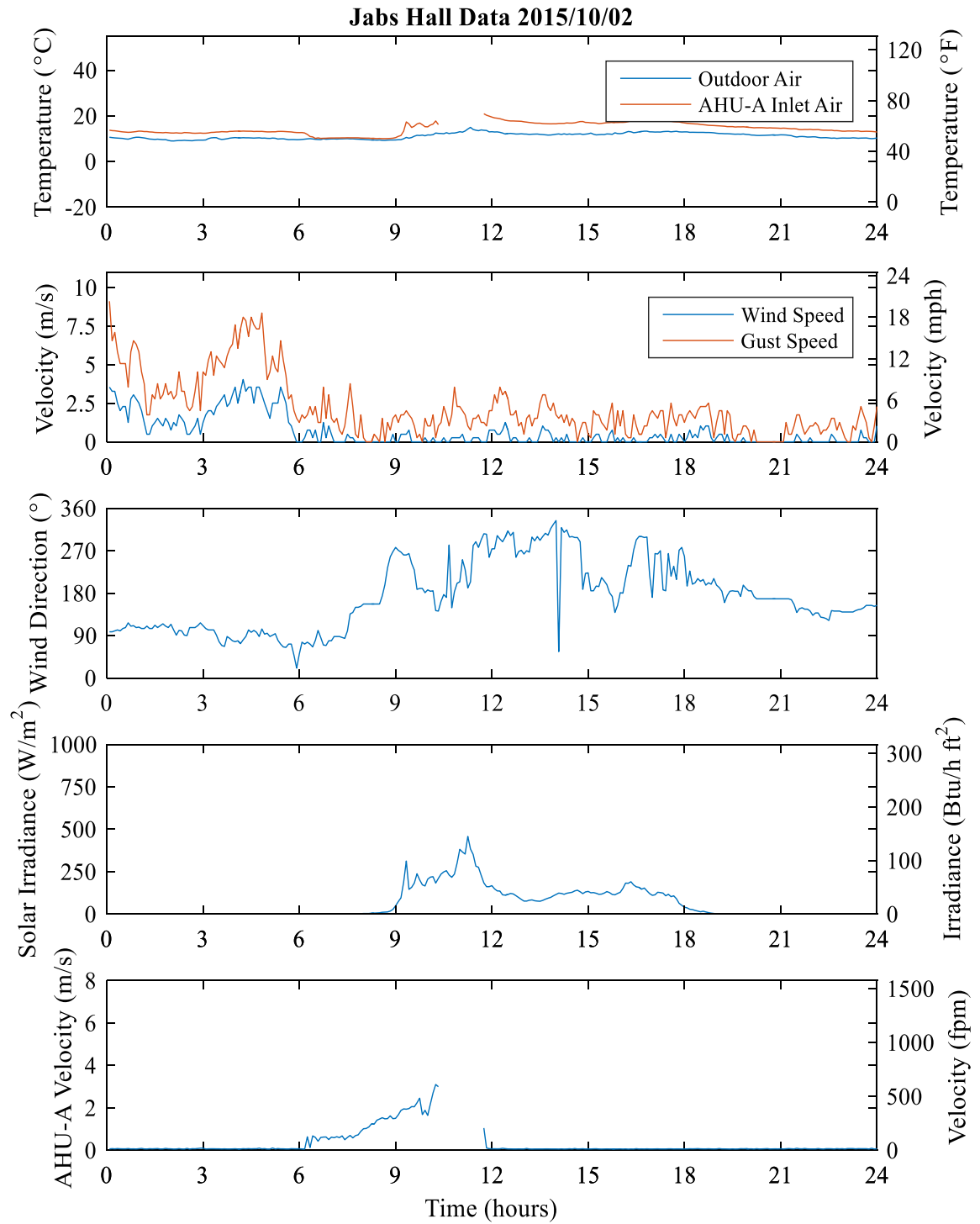


Figure 104: Jabs Hall Raw Data 2015/10/02

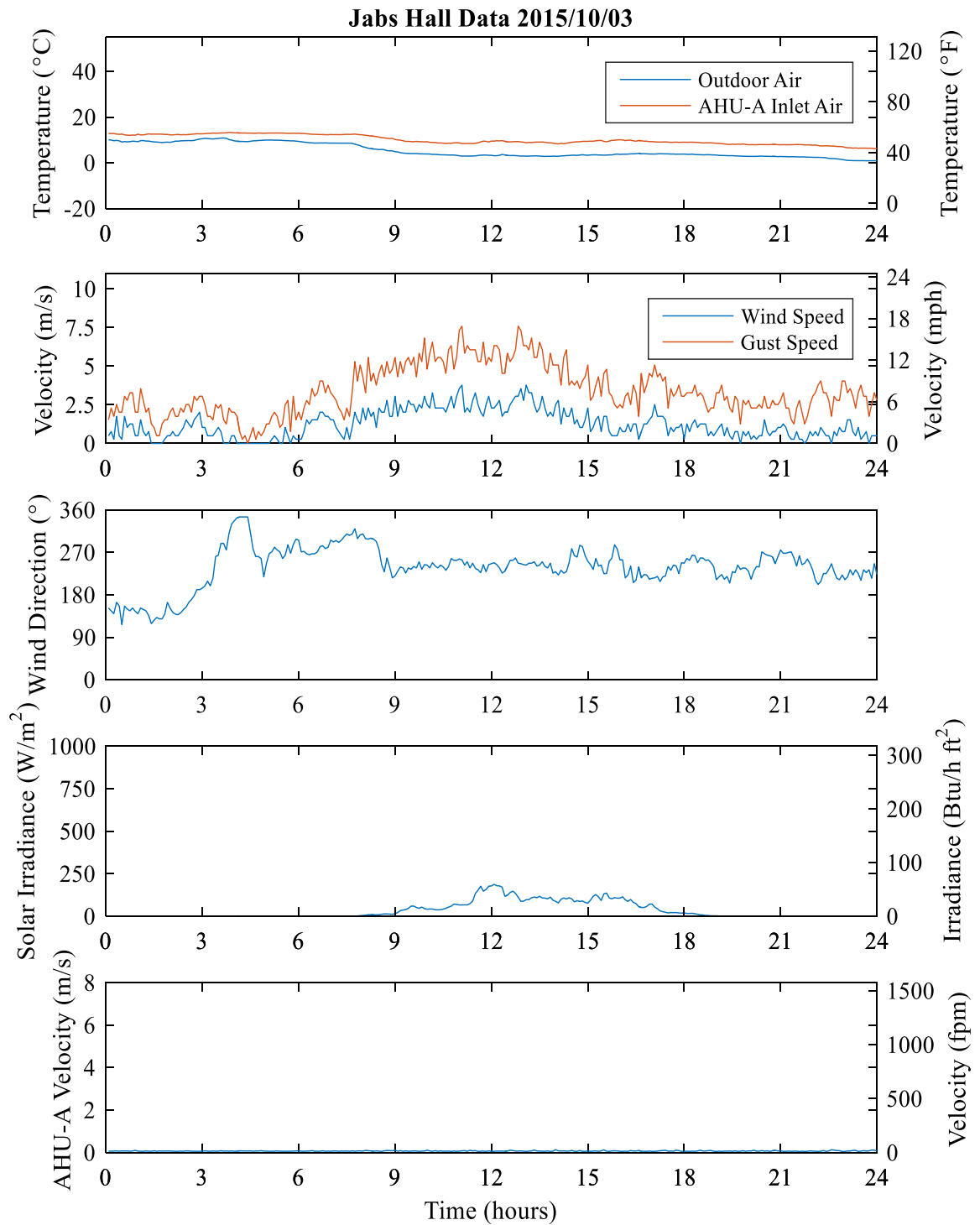


Figure 105: Jabs Hall Raw Data 2015/10/03

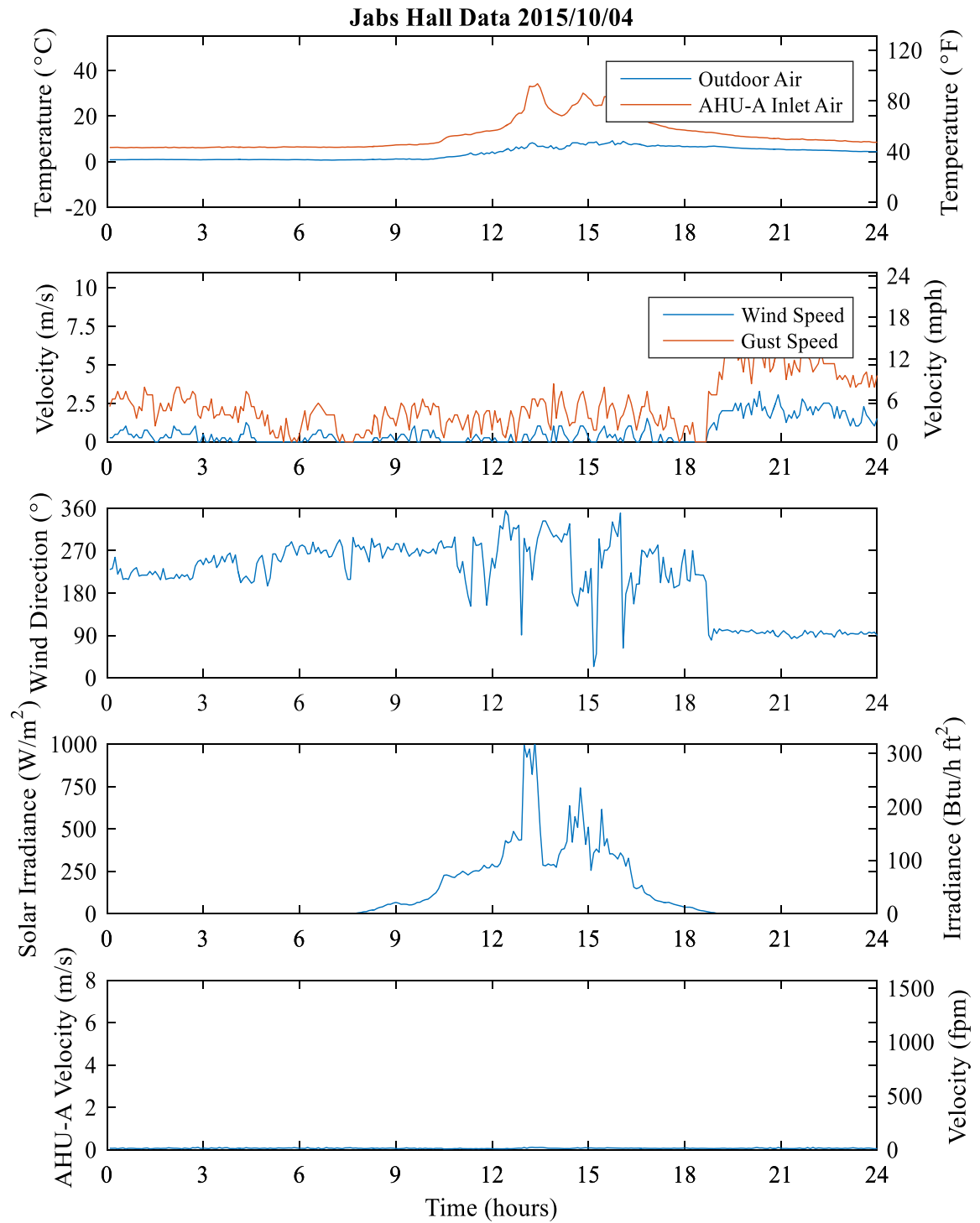


Figure 106: Jabs Hall Raw Data 2015/10/04

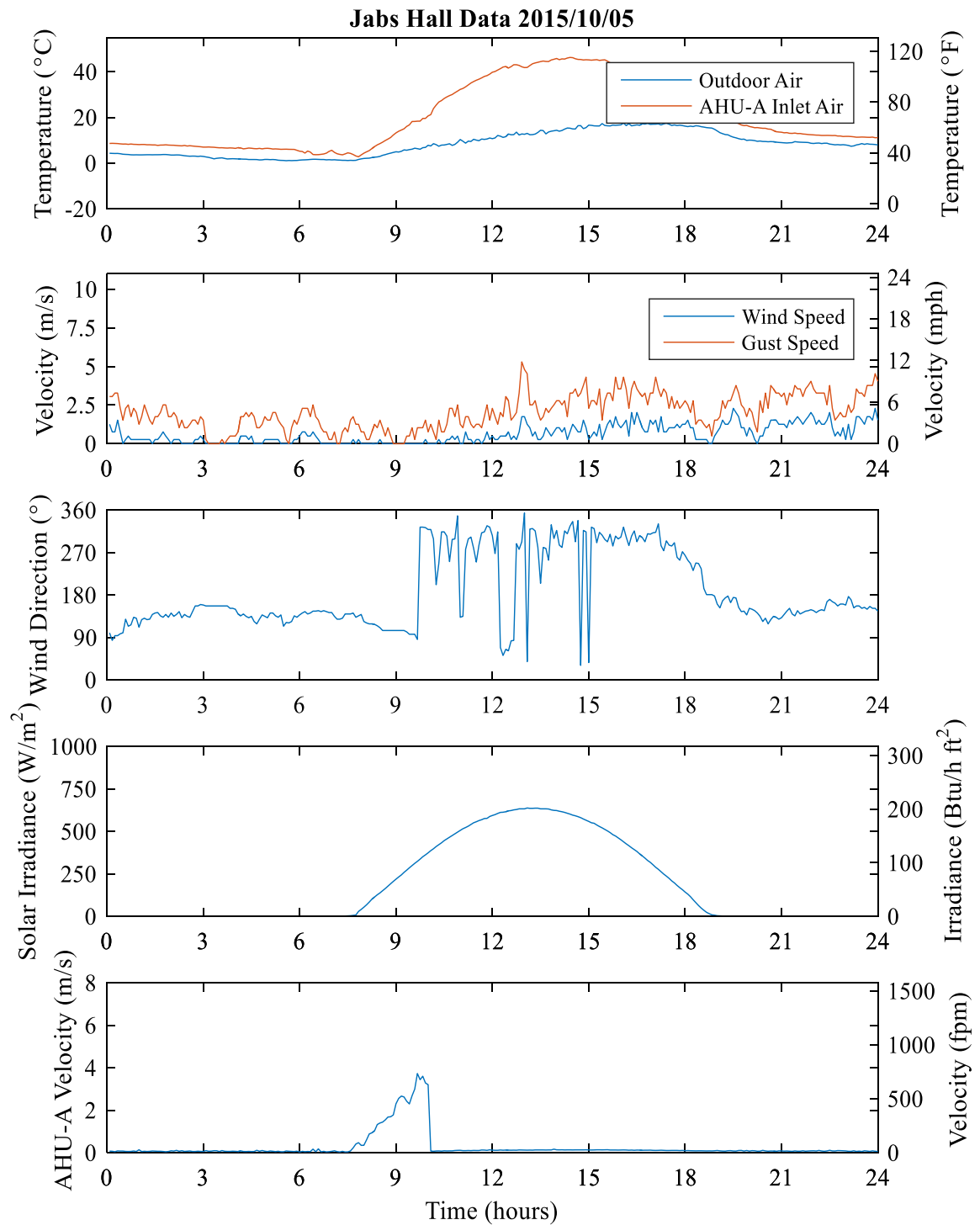


Figure 107: Jabs Hall Raw Data 2015/10/05

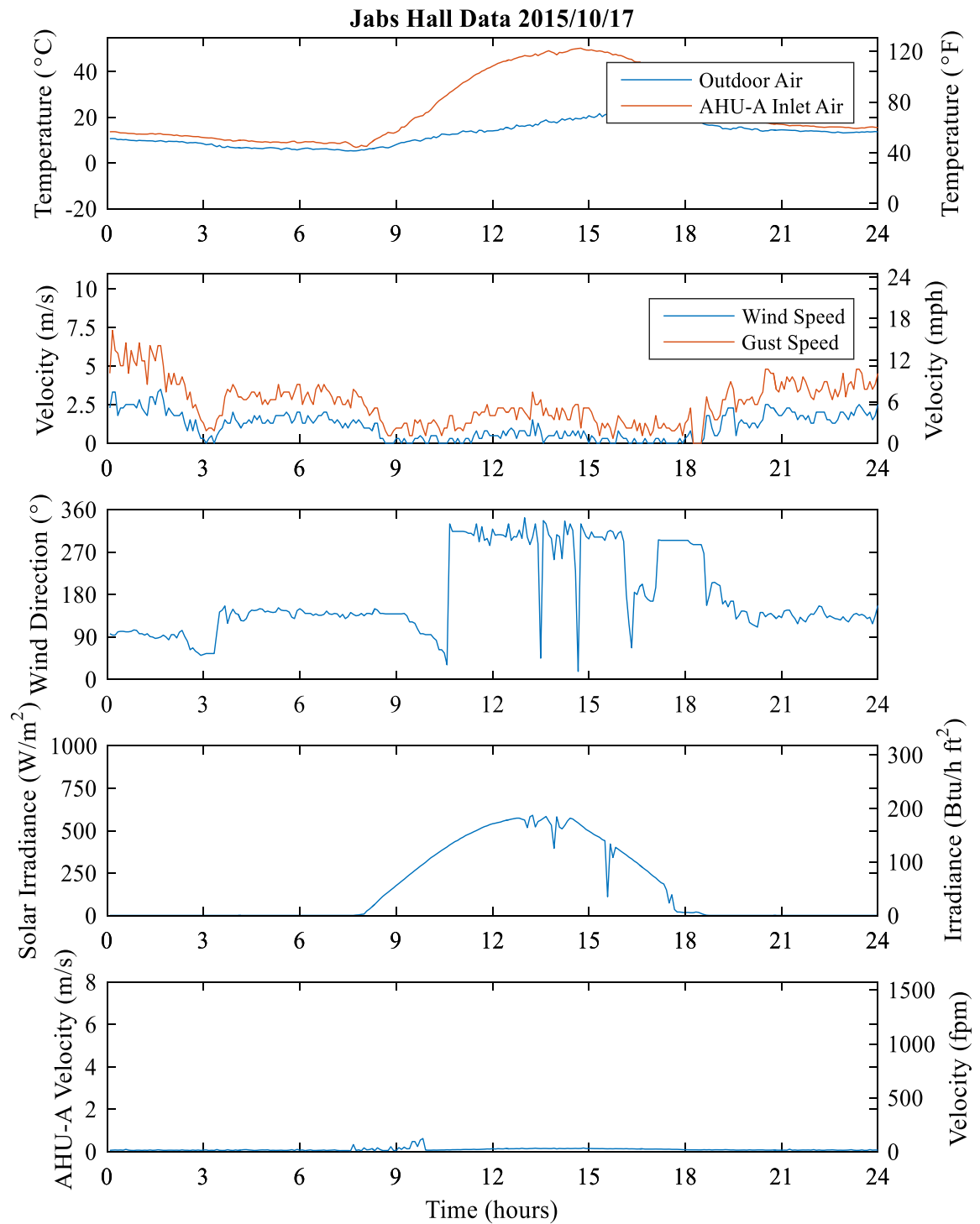


Figure 108: Jabs Hall Raw Data 2015/10/17

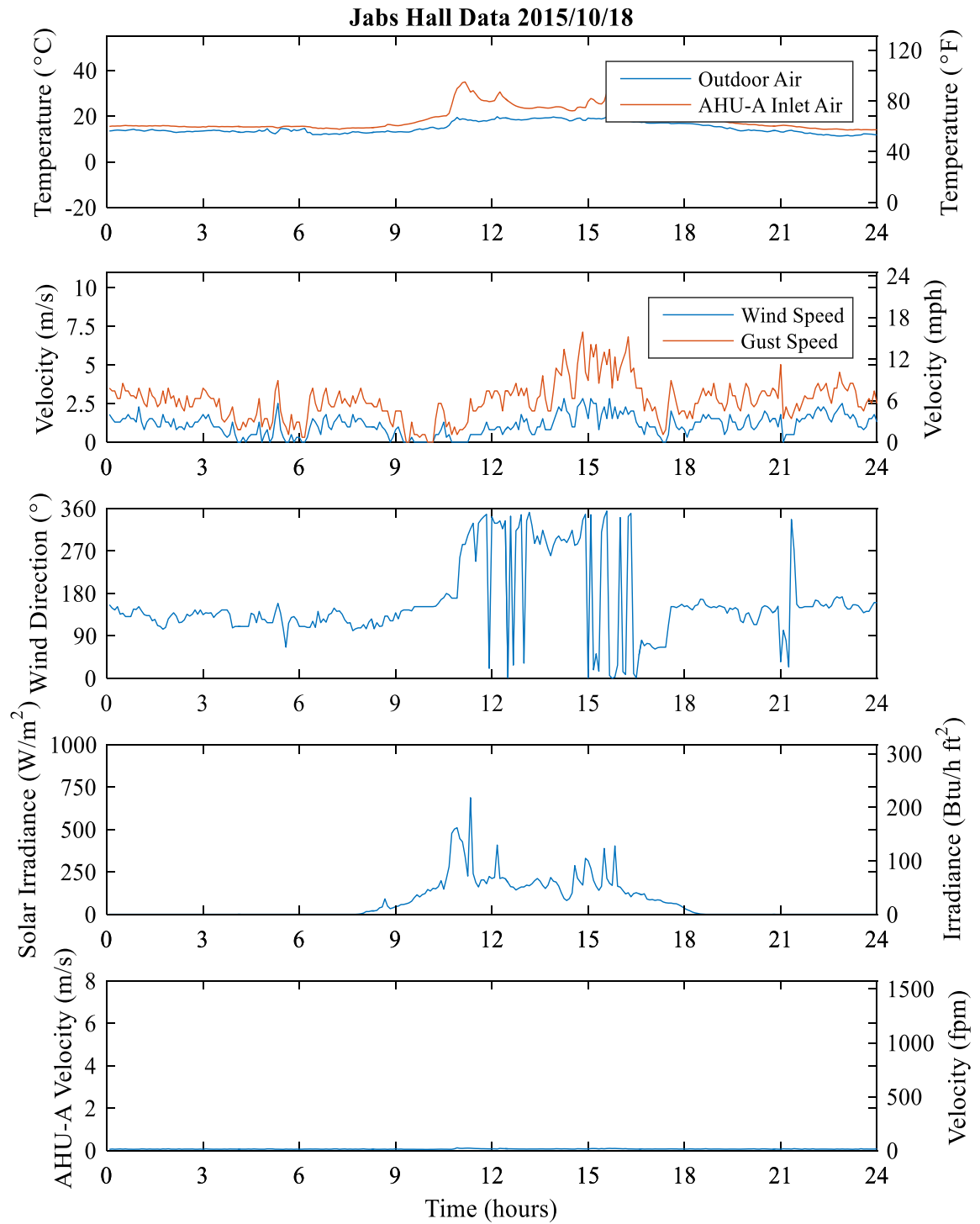


Figure 109: Jabs Hall Raw Data 2015/10/18

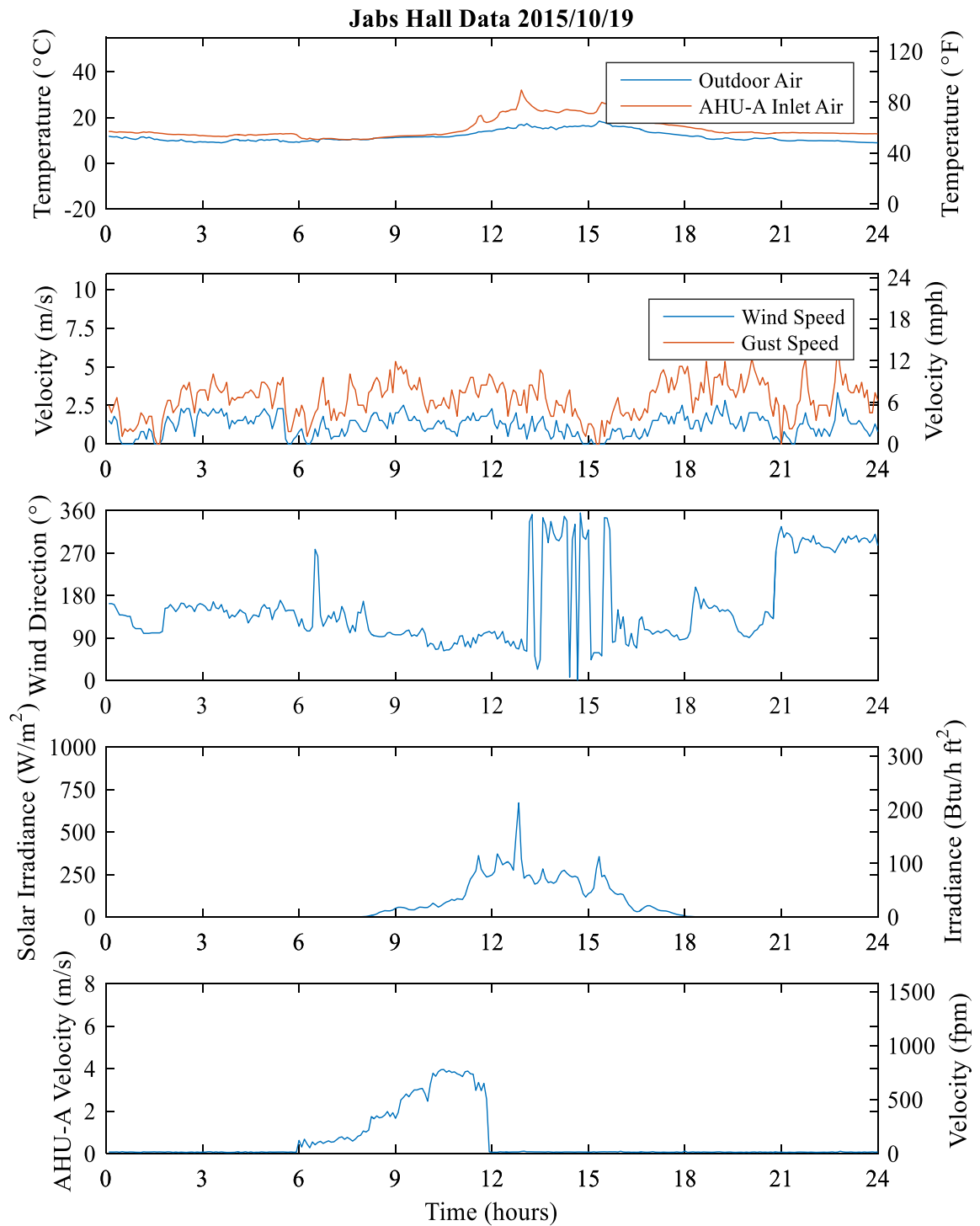


Figure 110: Jabs Hall Raw Data 2015/10/19

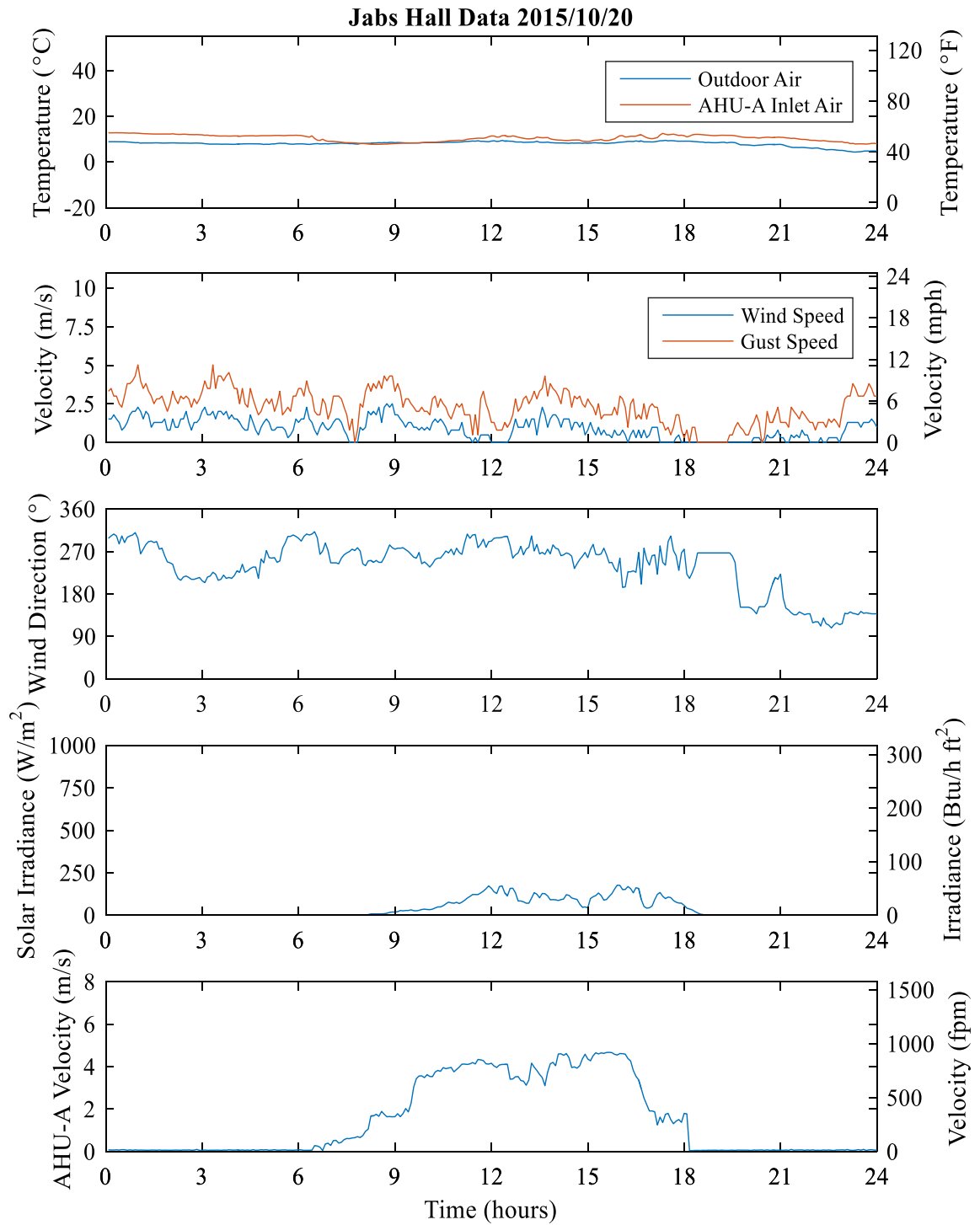


Figure 111: Jabs Hall Raw Data 2015/10/20

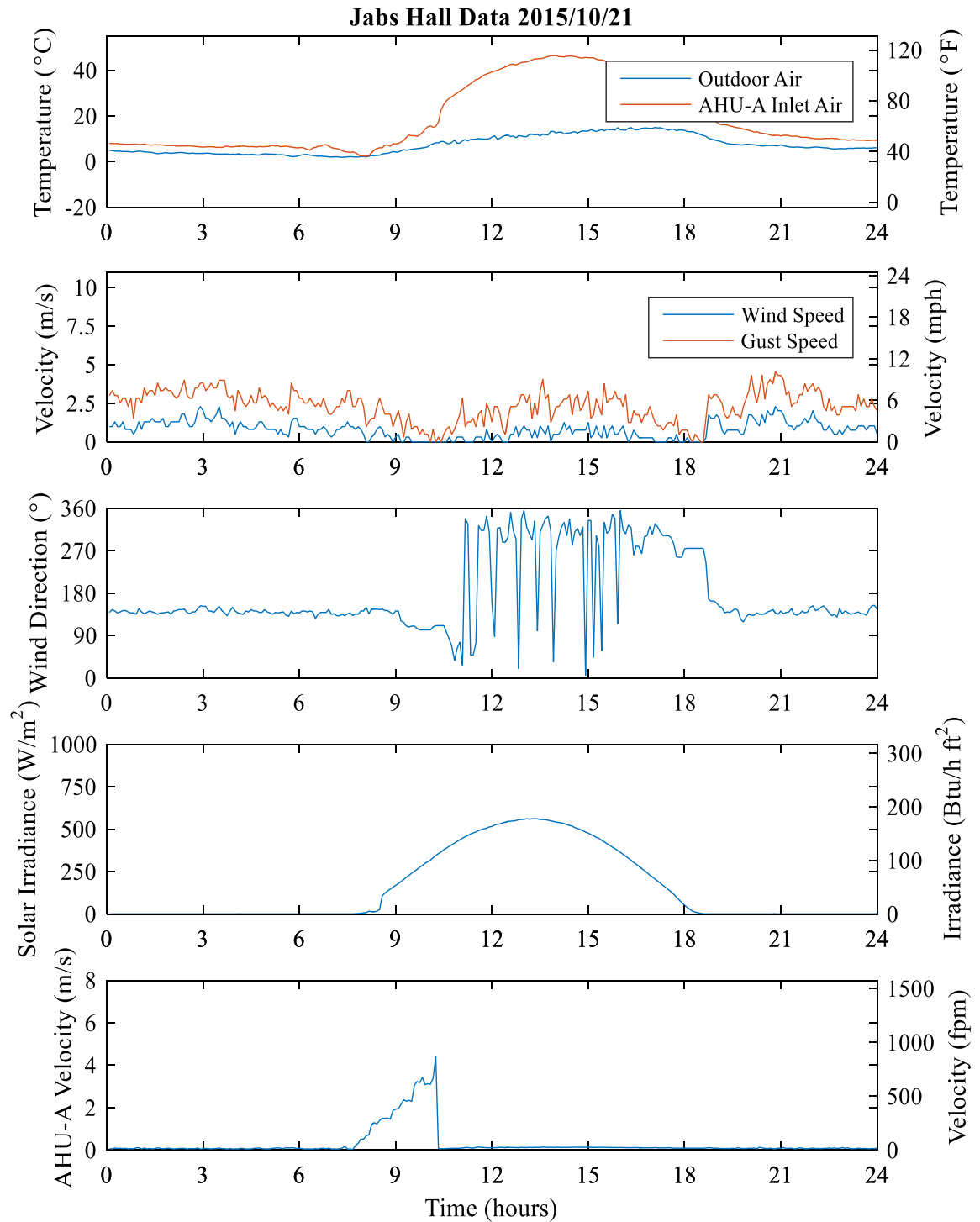


Figure 112: Jabs Hall Raw Data 2015/10/21

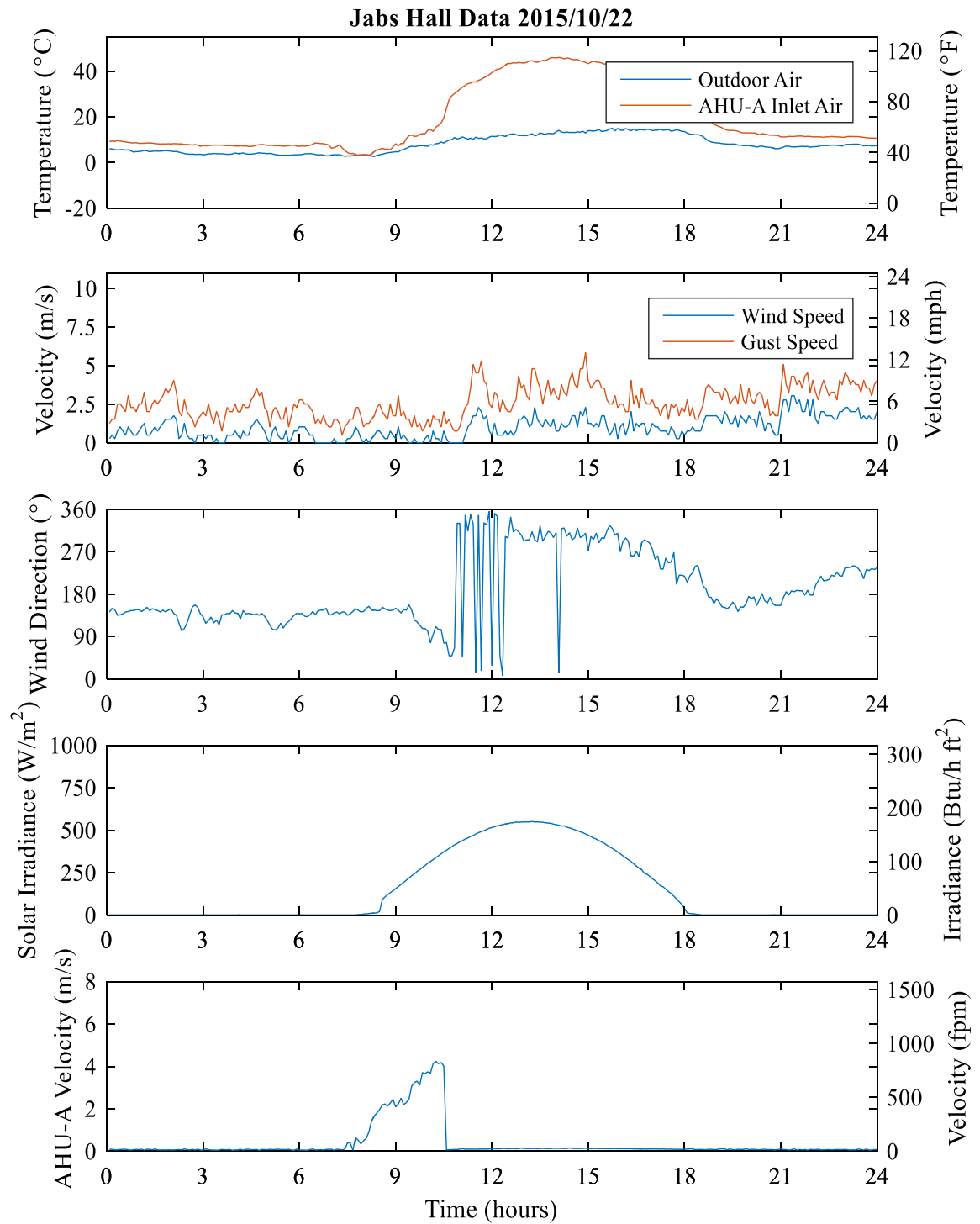


Figure 113: Jabs Hall Raw Data 2015/10/22

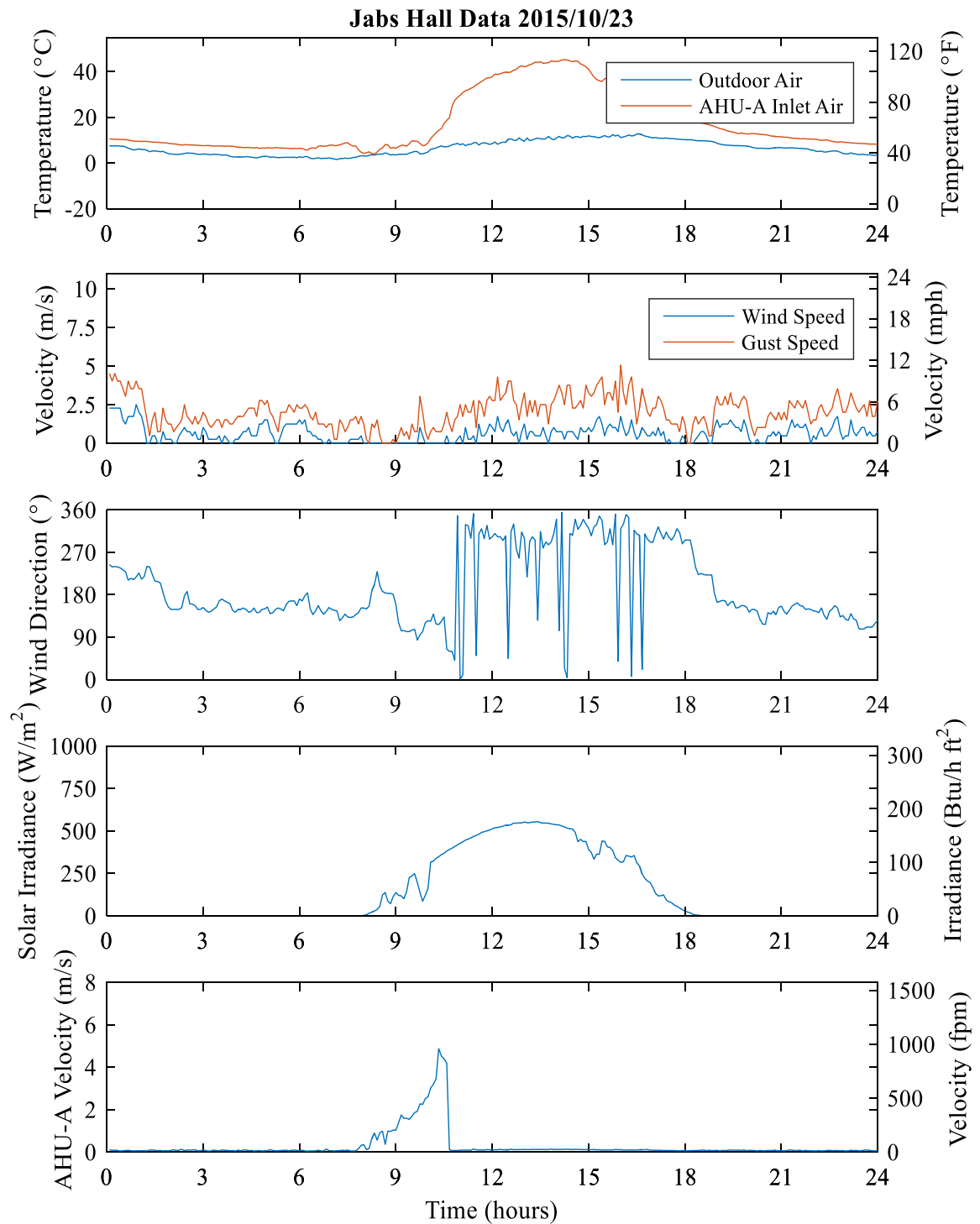


Figure 114: Jabs Hall Raw Data 2015/10/23

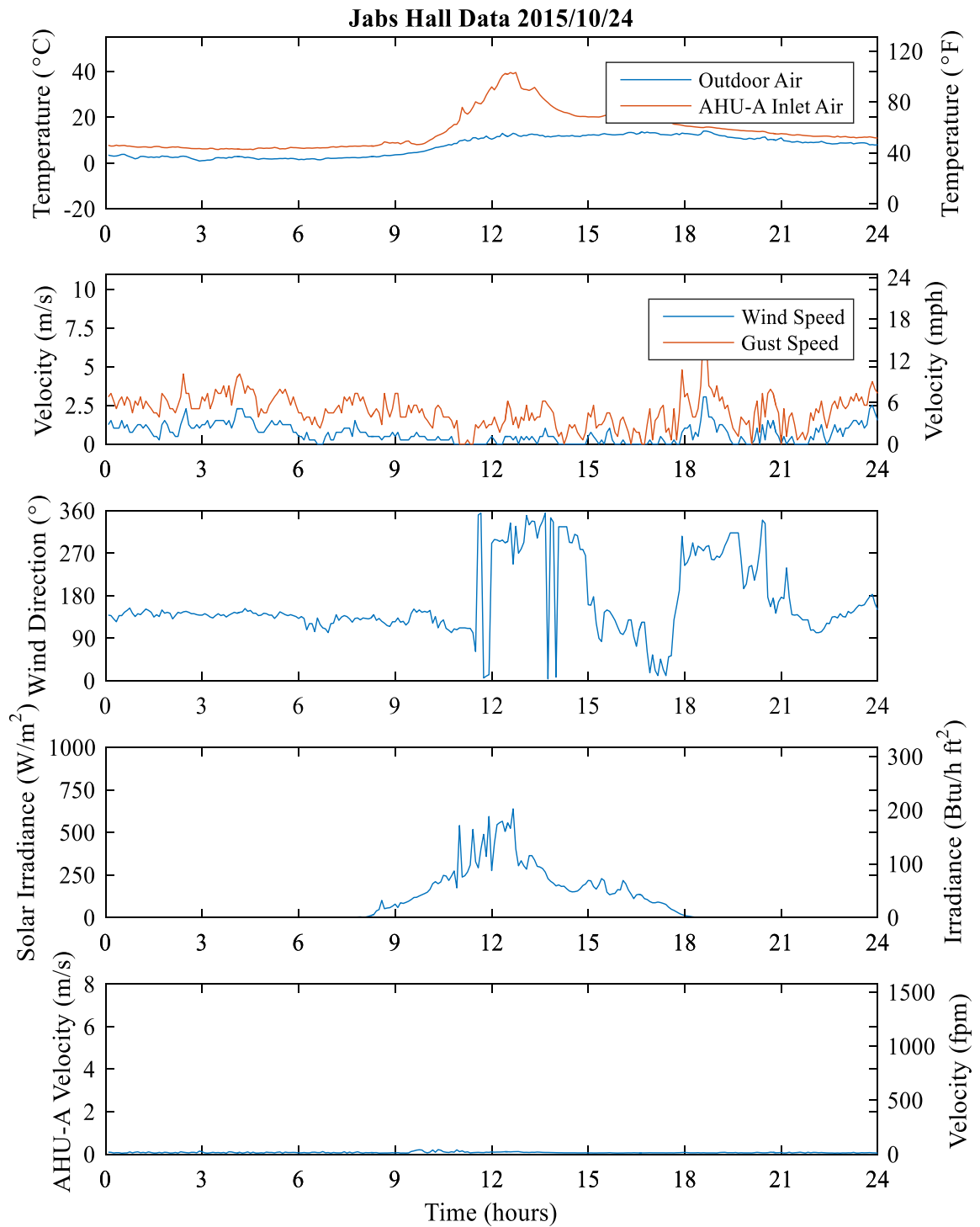


Figure 115: Jabs Hall Raw Data 2015/10/24

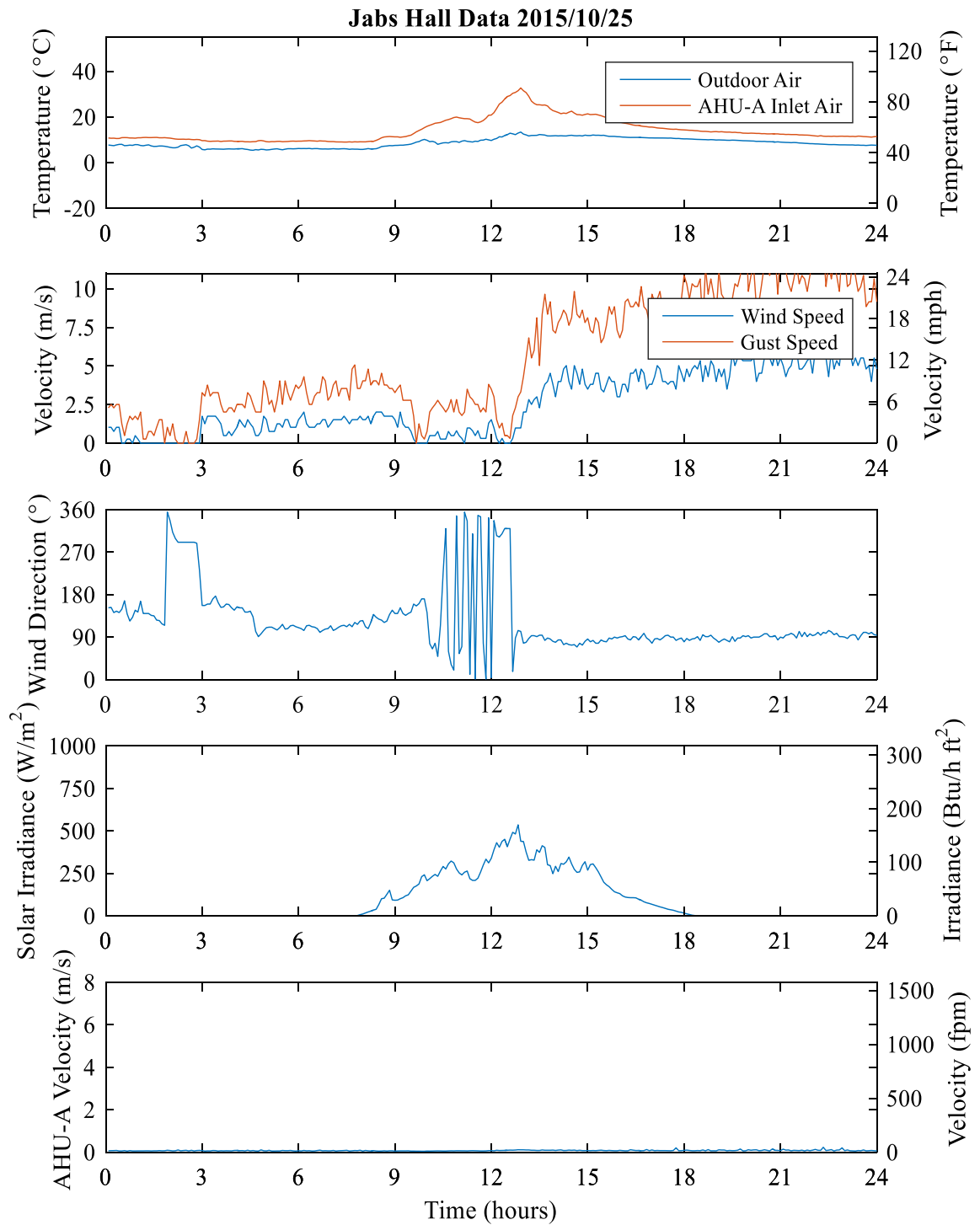


Figure 116: Jabs Hall Raw Data 2015/10/25

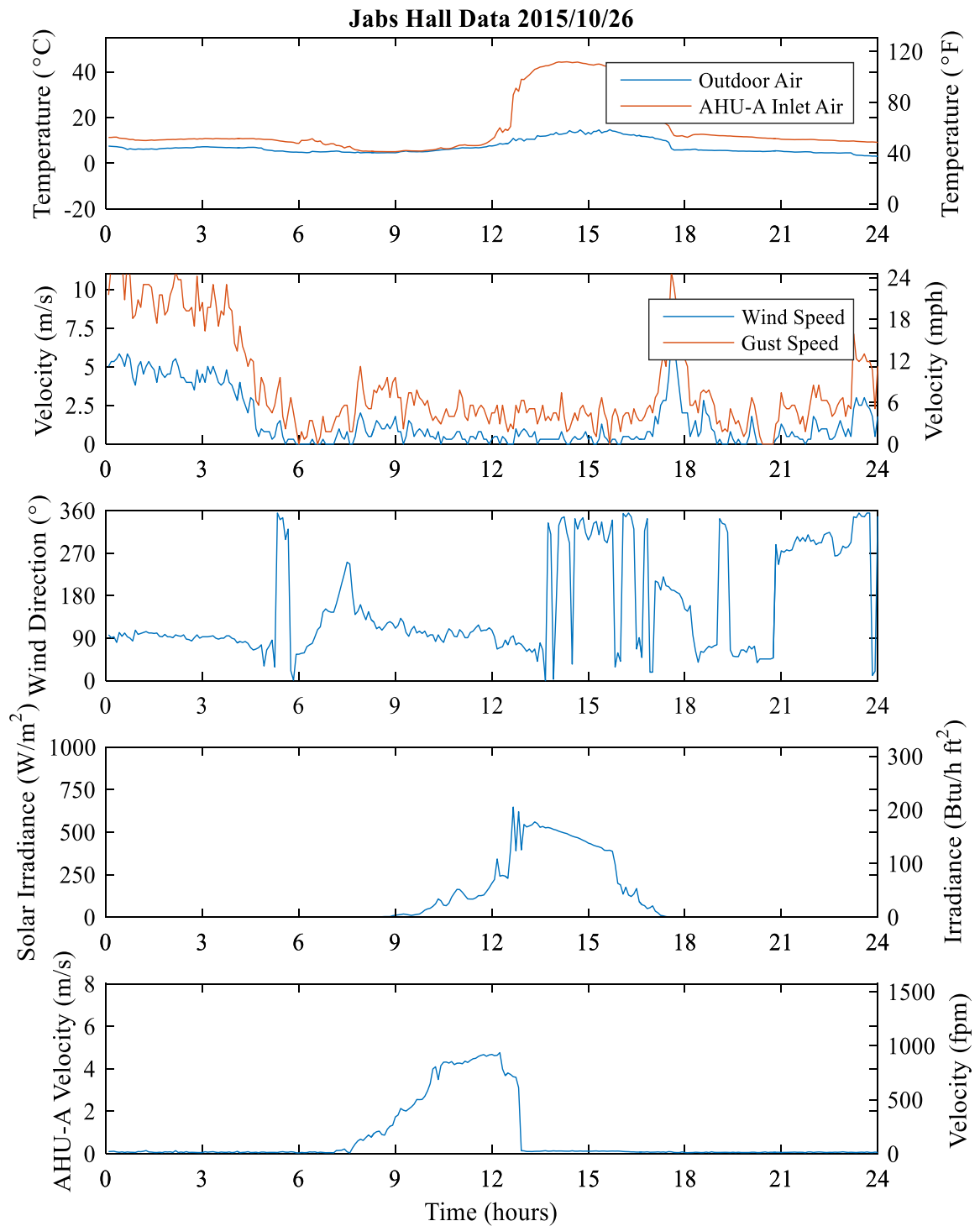


Figure 117: Jabs Hall Raw Data 2015/10/26

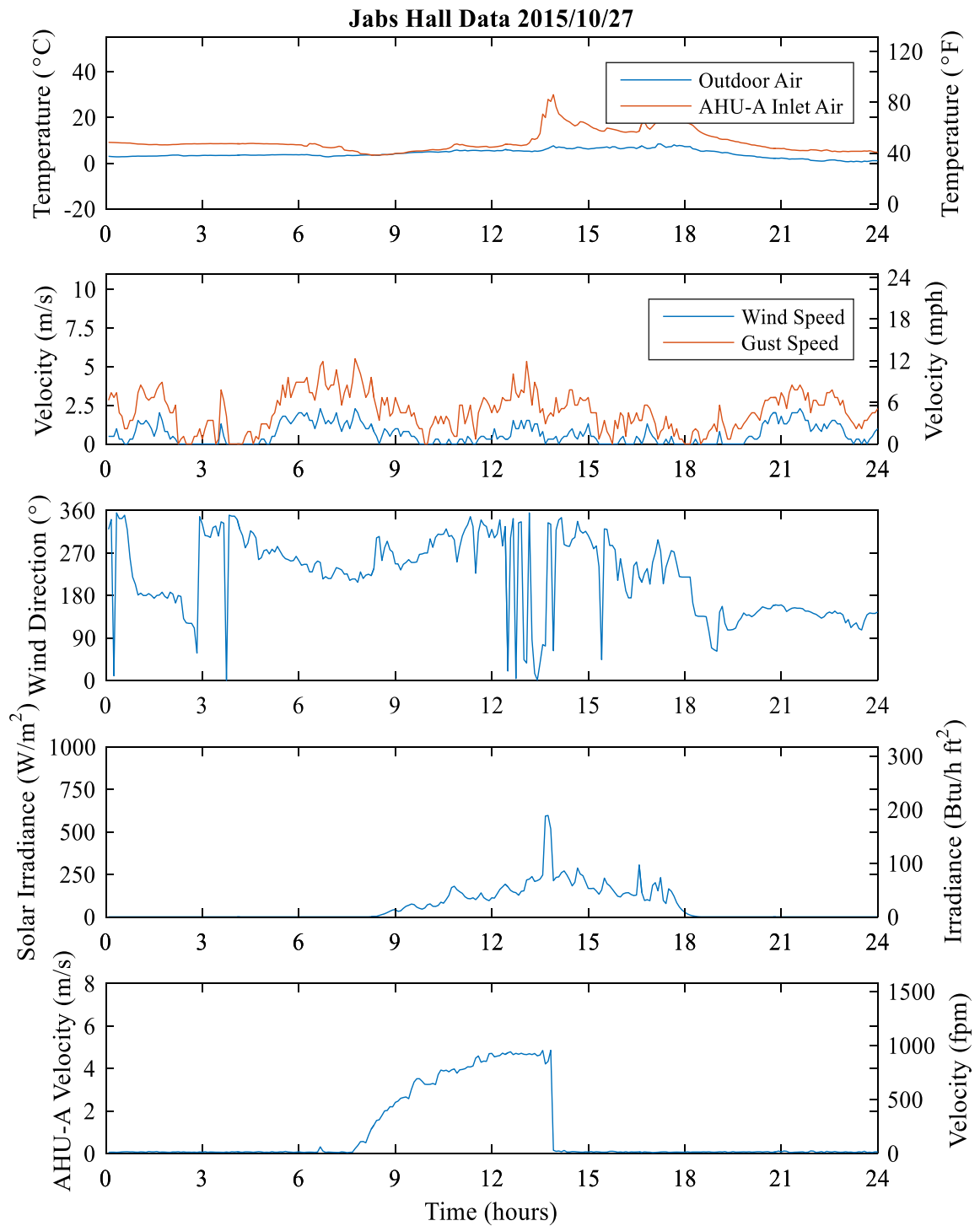


Figure 118: Jabs Hall Raw Data 2015/10/27

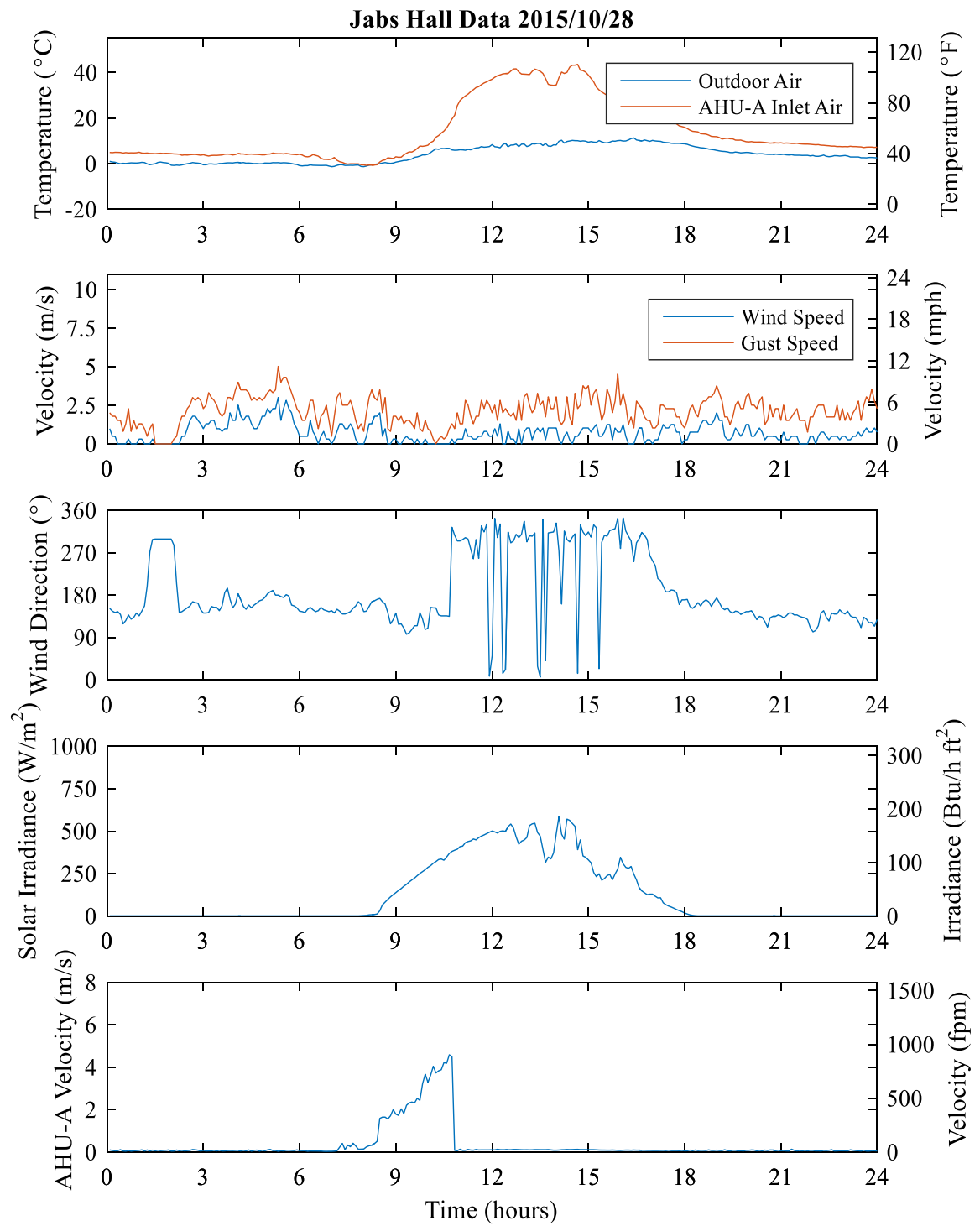


Figure 119: Jabs Hall Raw Data 2015/10/28

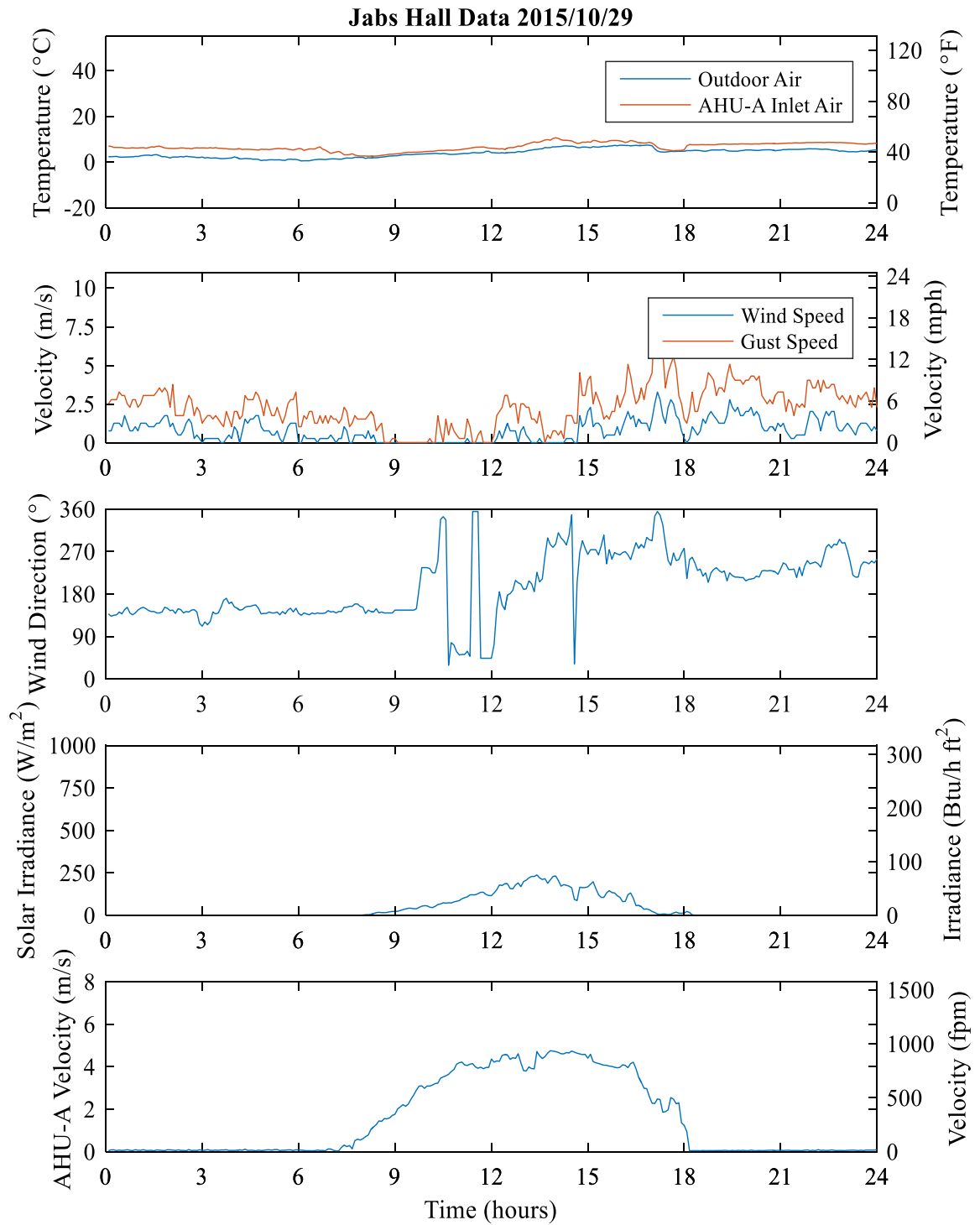


Figure 120: Jabs Hall Raw Data 2015/10/29

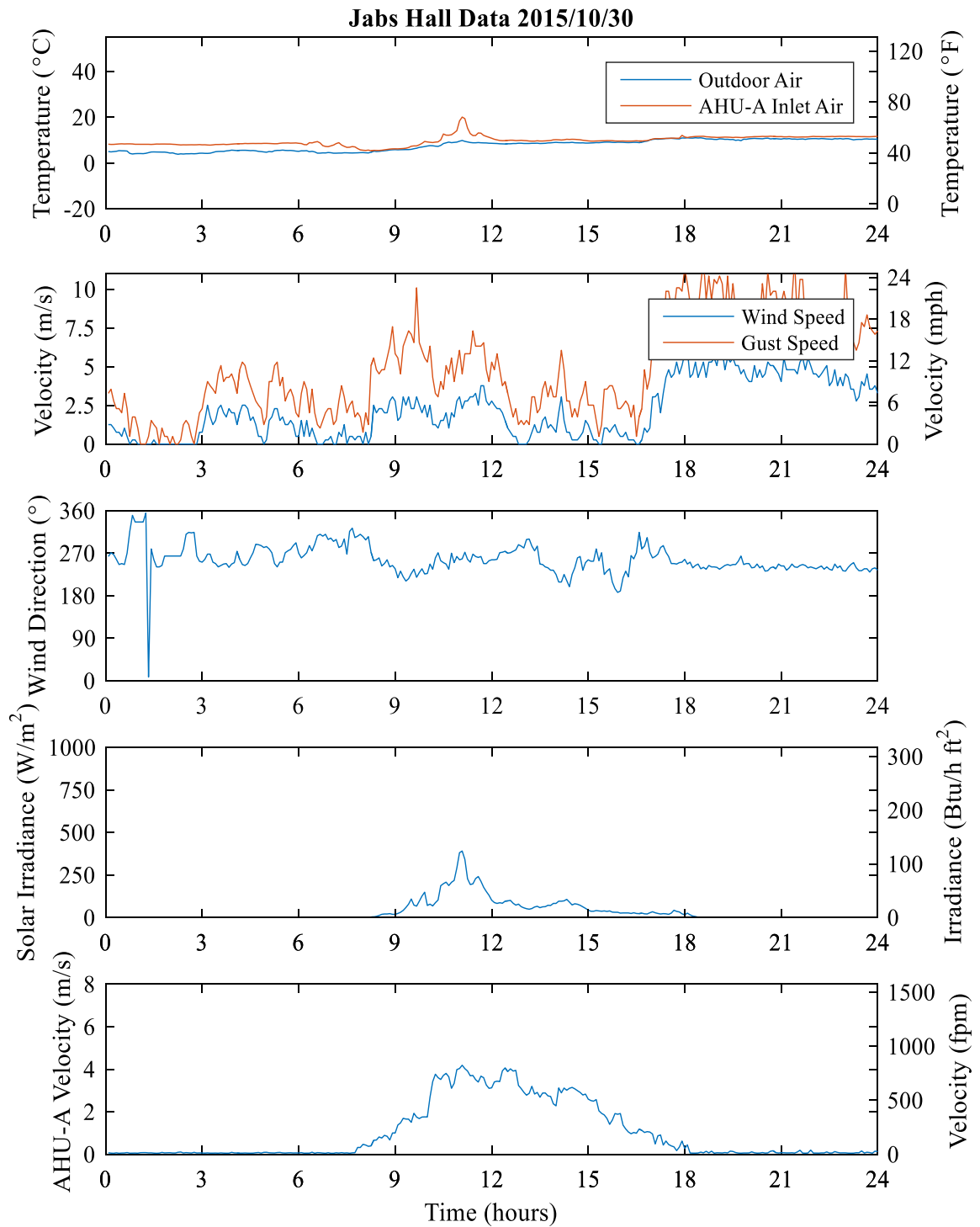


Figure 121: Jabs Hall Raw Data 2015/10/30

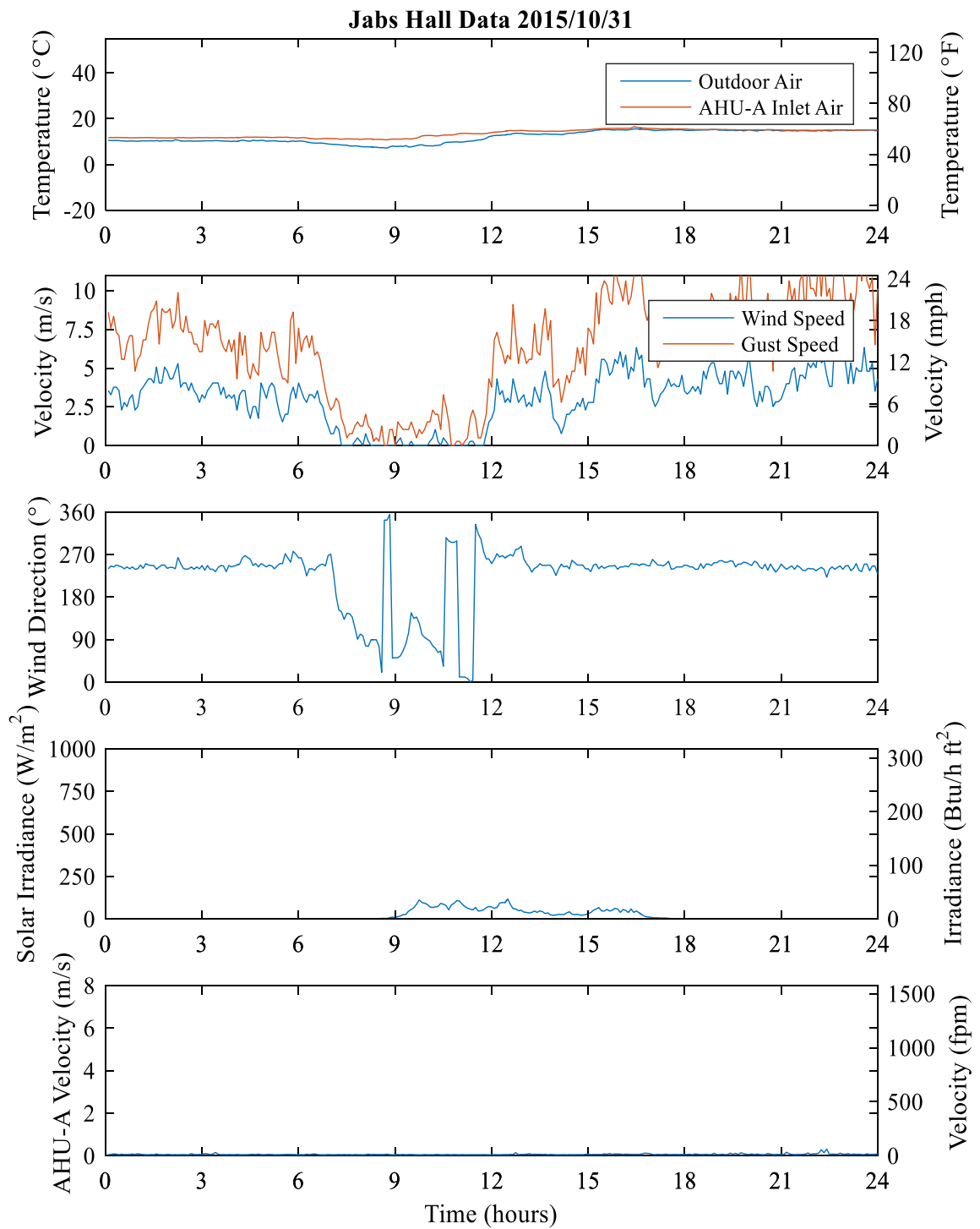


Figure 122: Jabs Hall Raw Data 2015/10/31

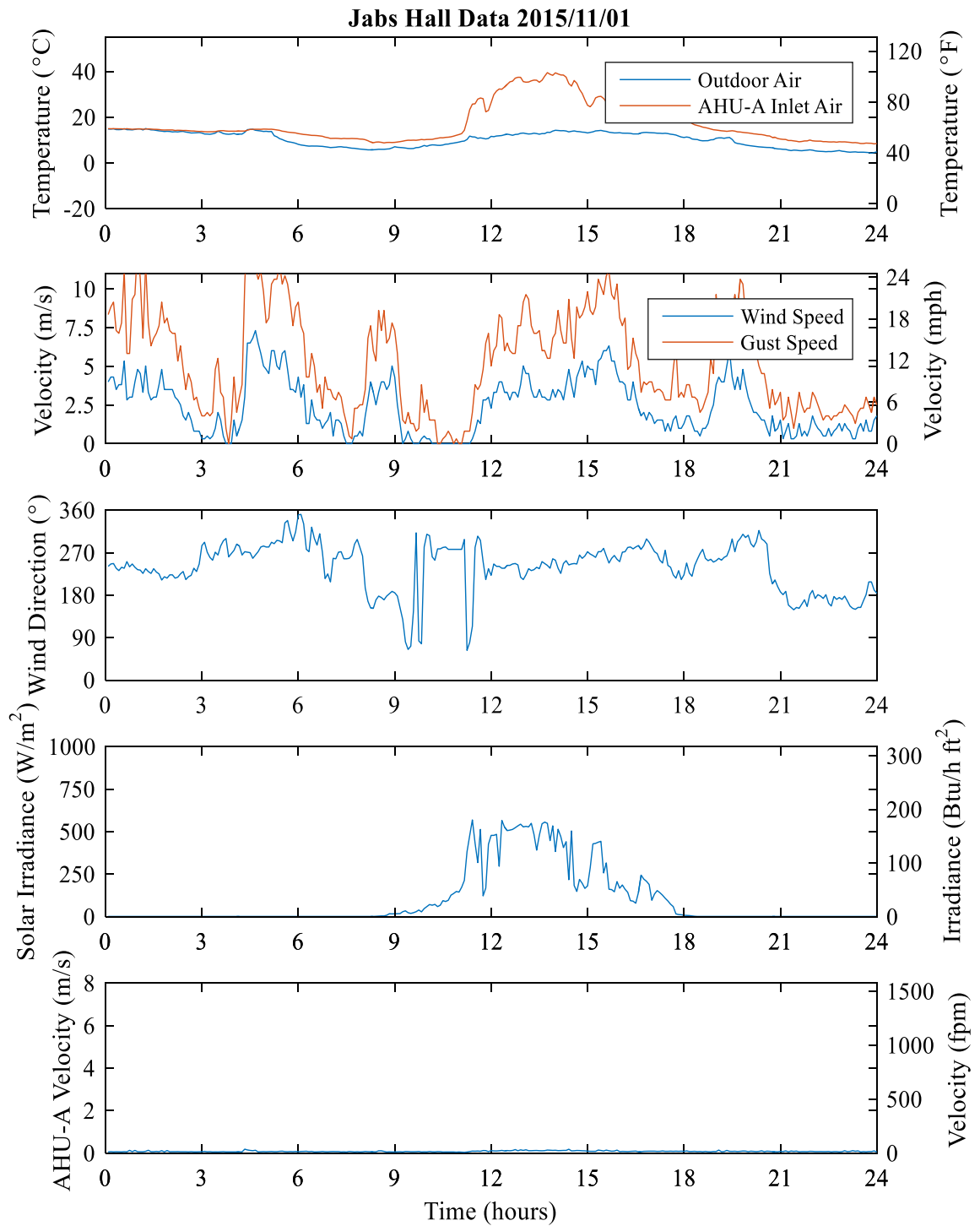


Figure 123: Jabs Hall Raw Data 2015/11/01

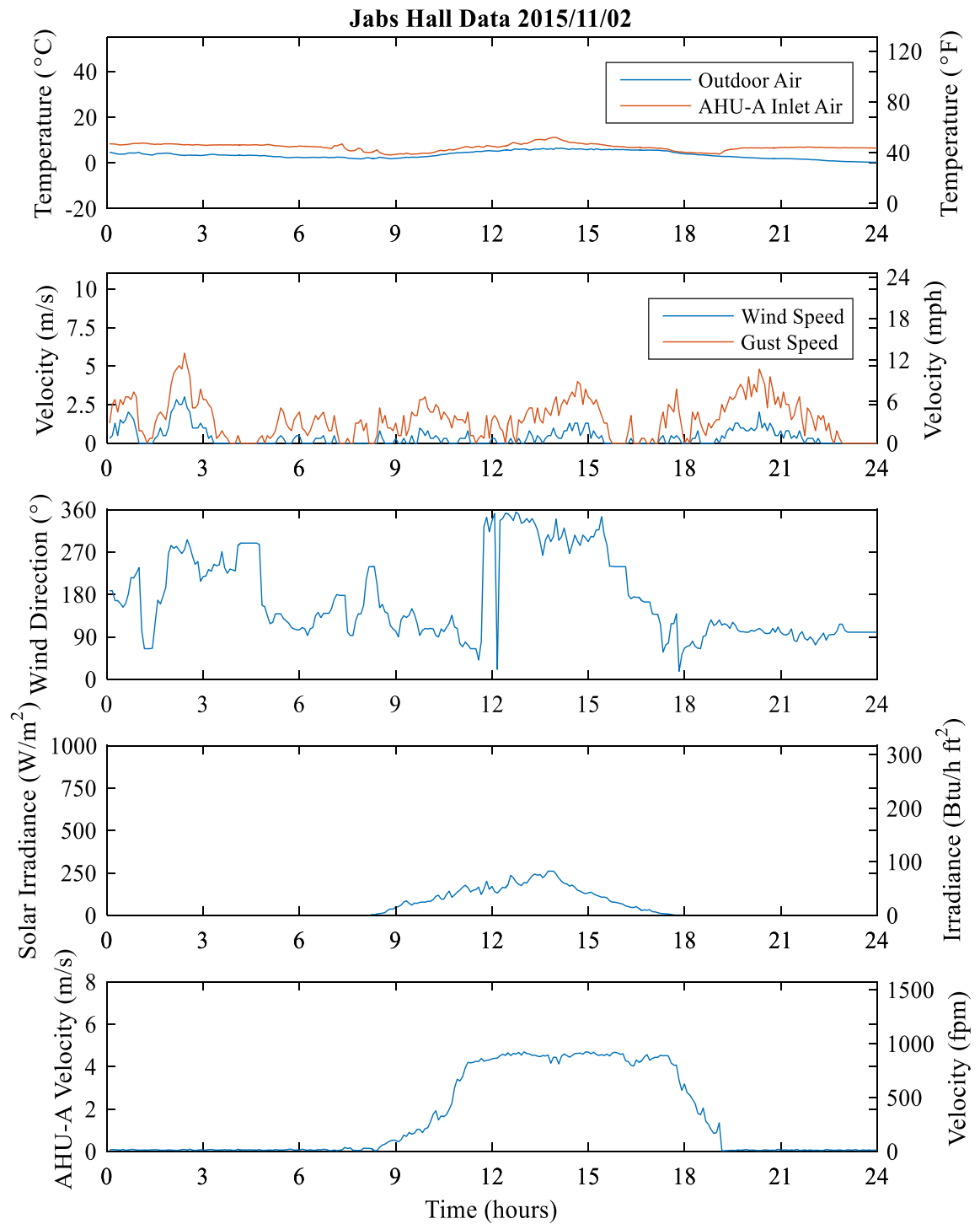


Figure 124: Jabs Hall Raw Data 2015/11/02

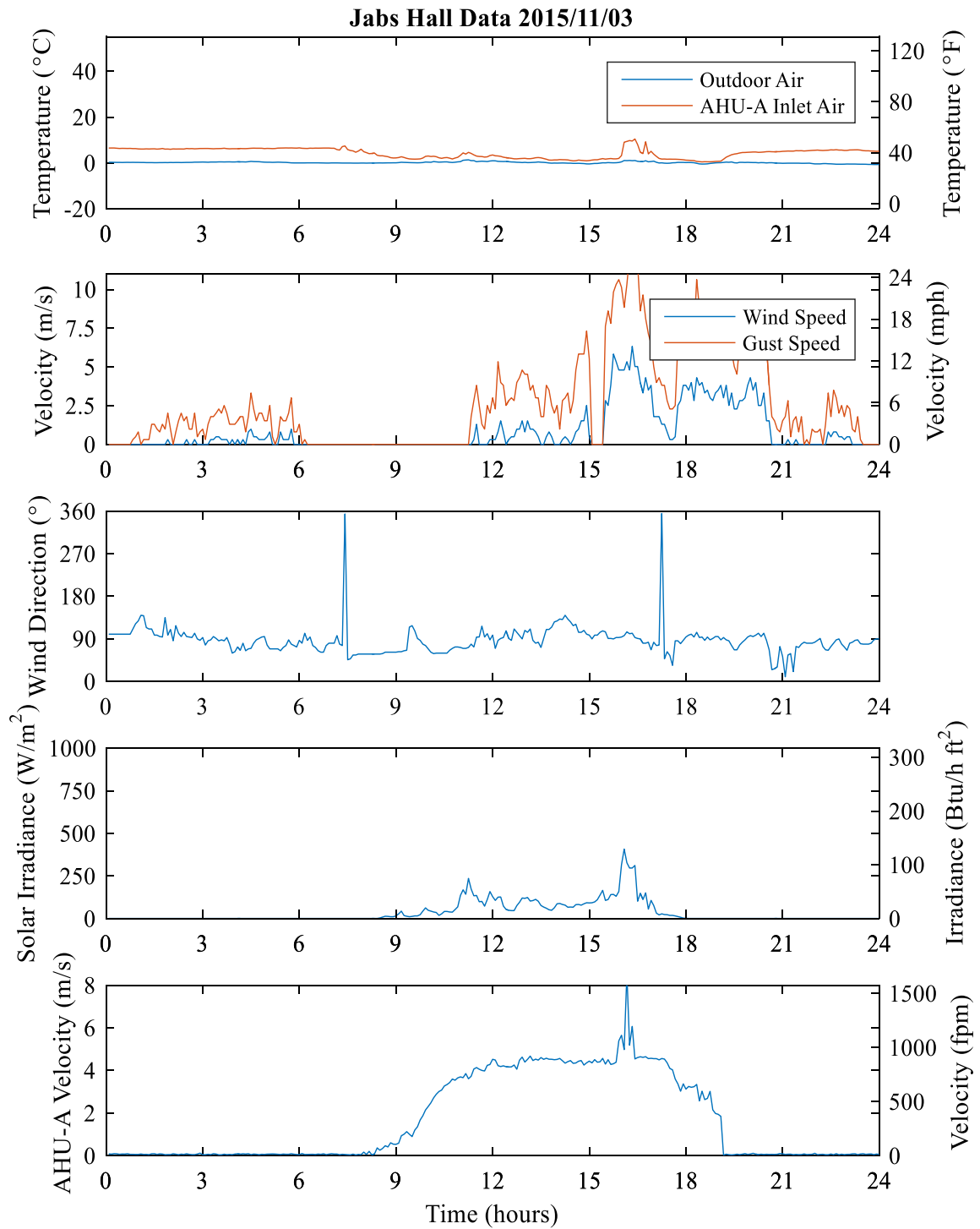


Figure 125: Jabs Hall Raw Data 2015/11/03

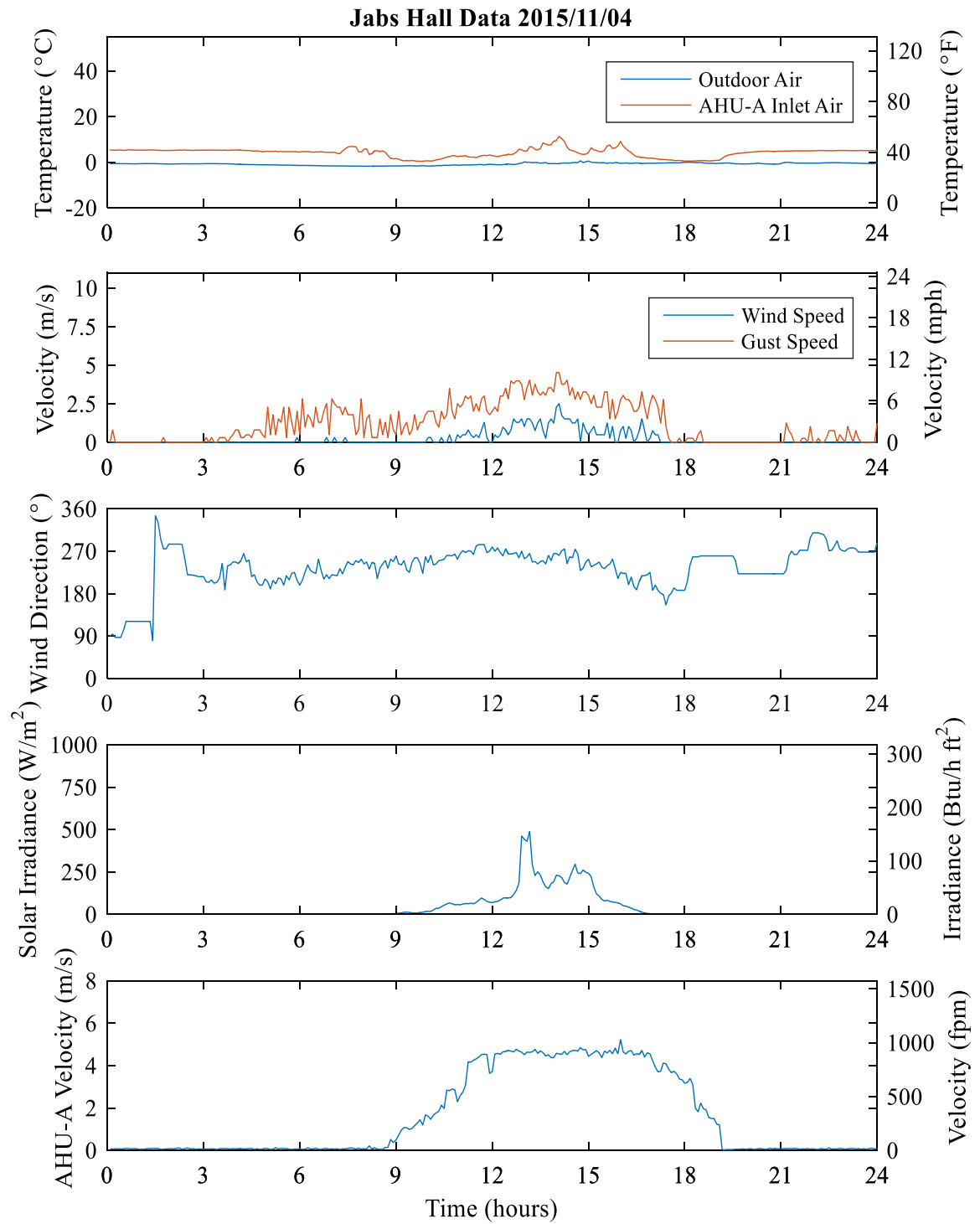


Figure 126: Jabs Hall Raw Data 2015/11/04

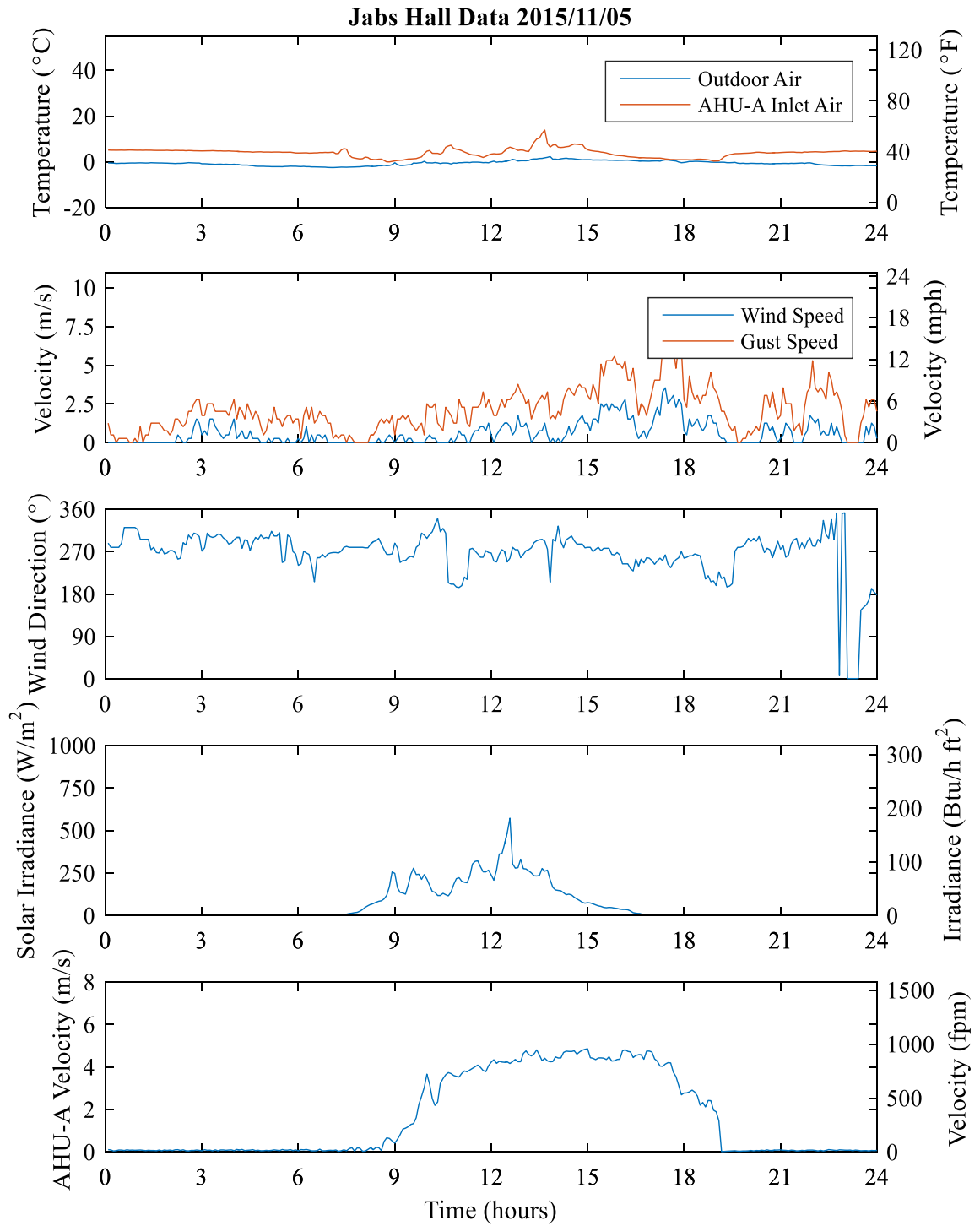


Figure 127: Jabs Hall Raw Data 2015/11/05

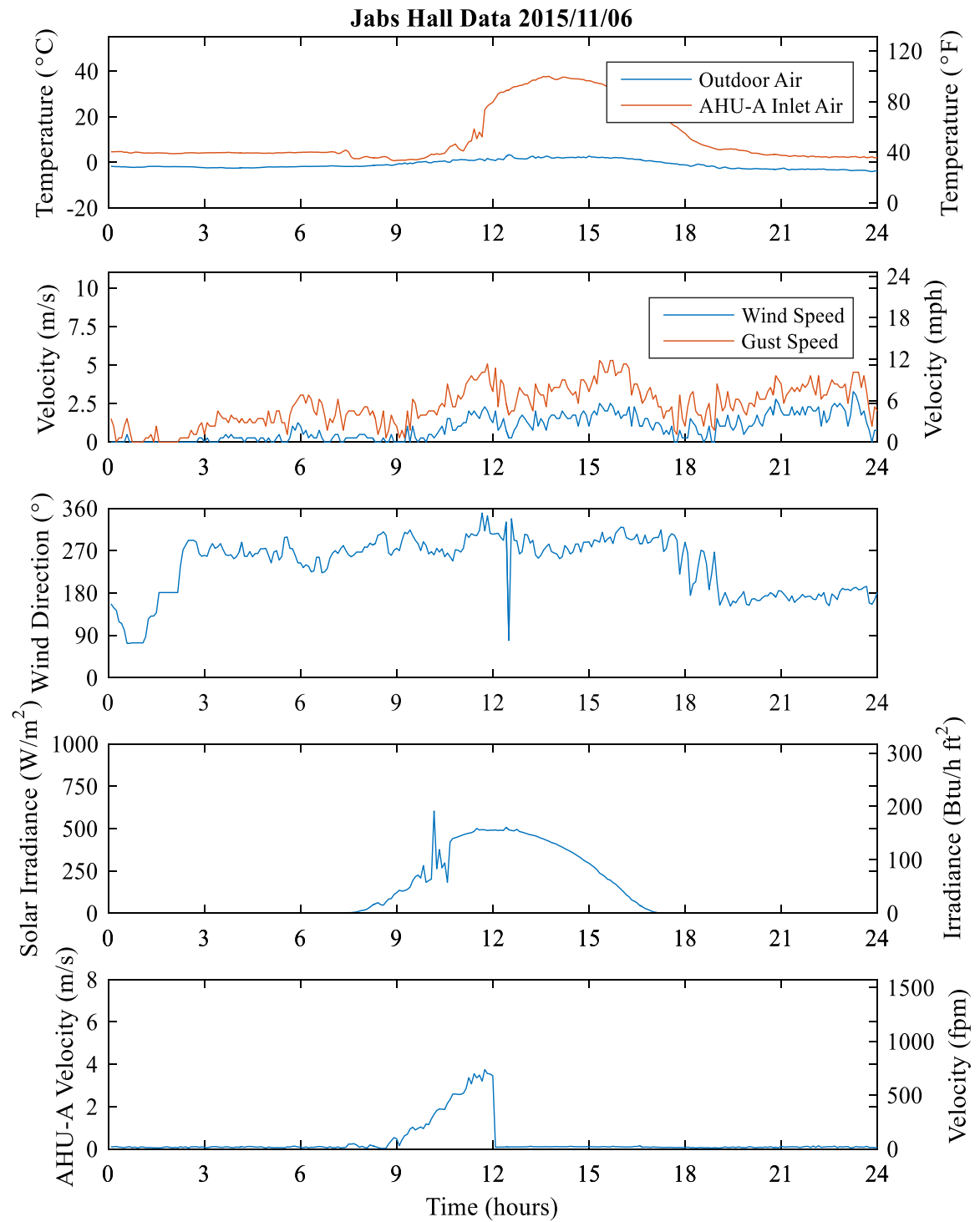


Figure 128: Jabs Hall Raw Data 2015/11/06

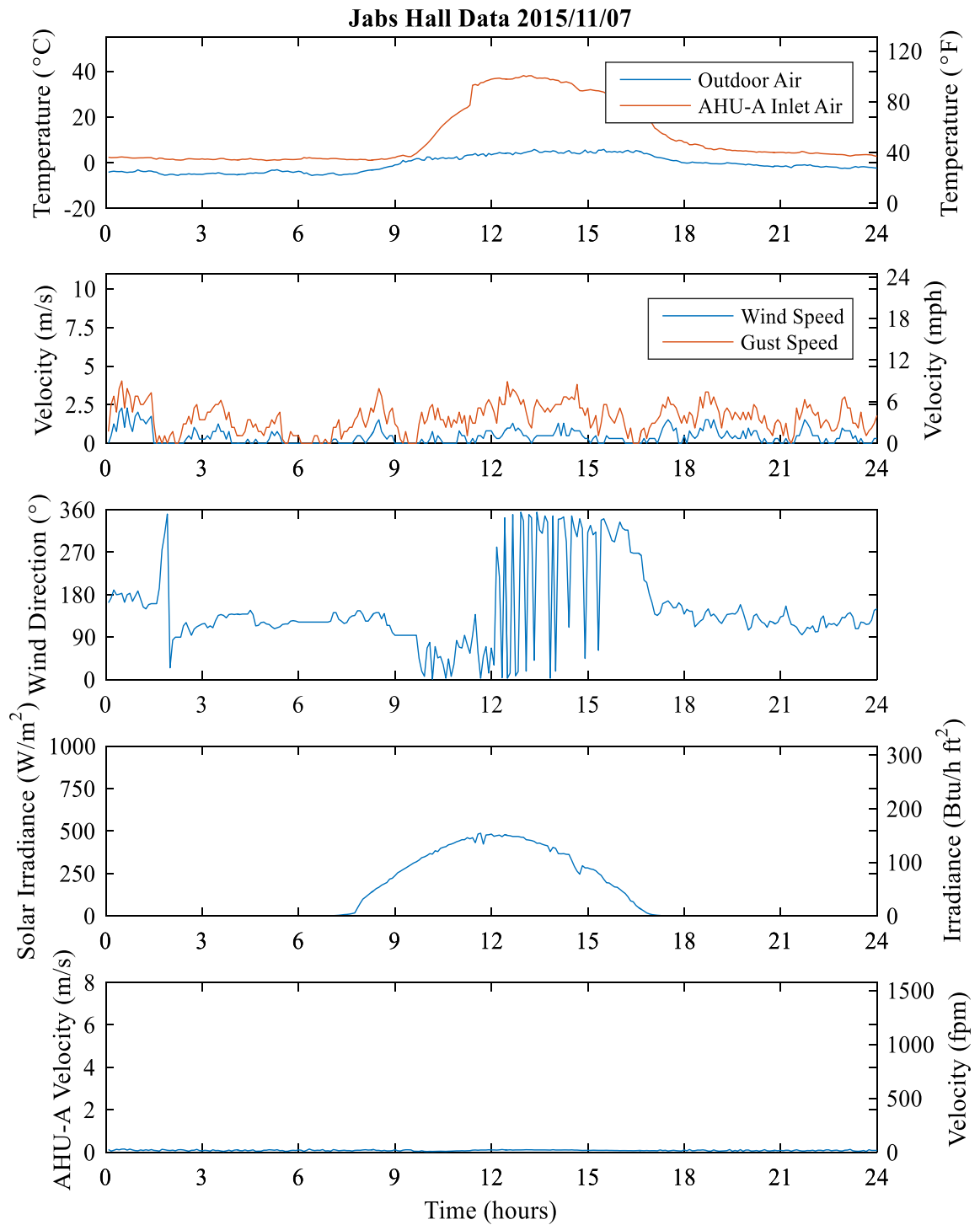


Figure 129: Jabs Hall Raw Data 2015/11/07

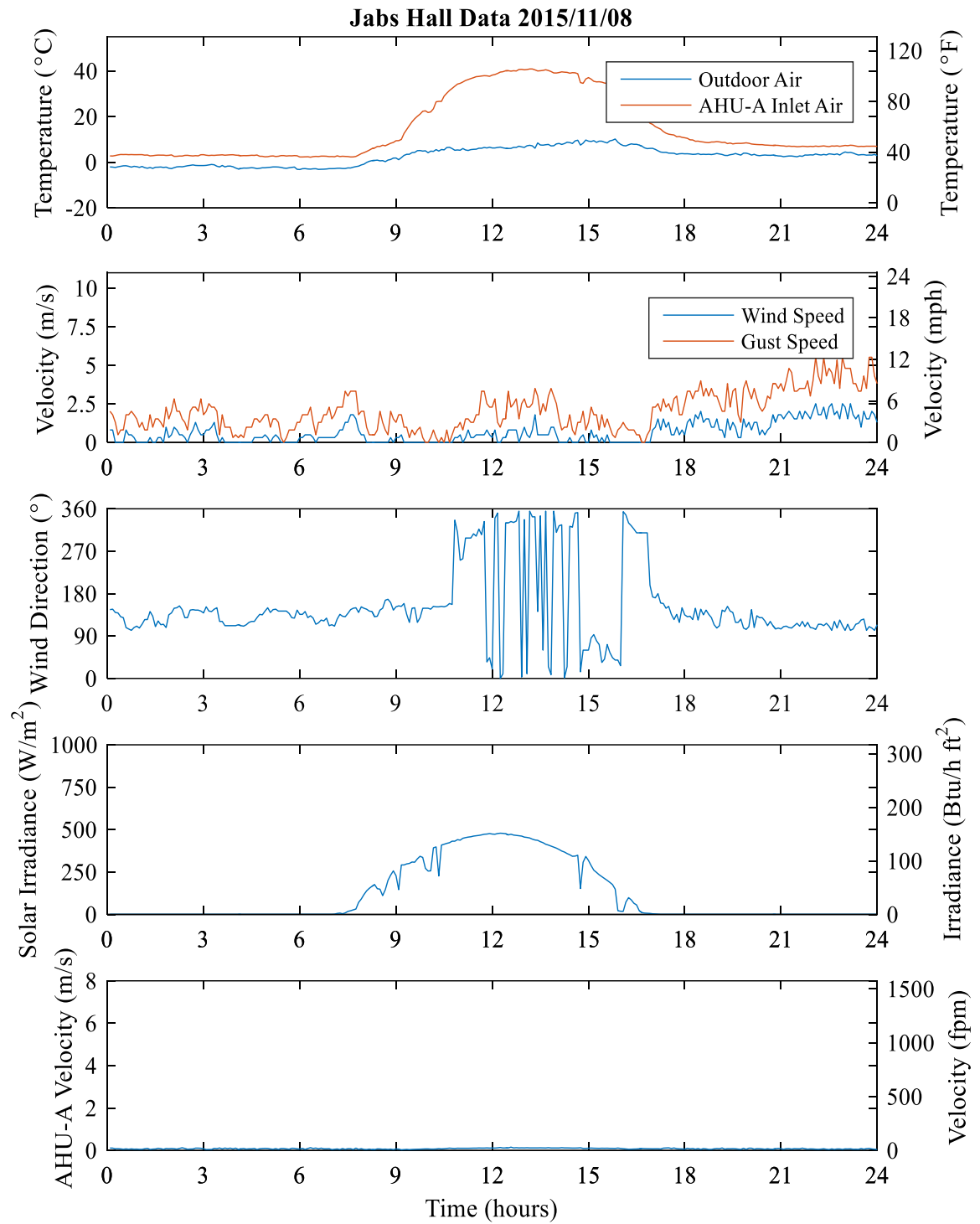


Figure 130: Jabs Hall Raw Data 2015/11/08

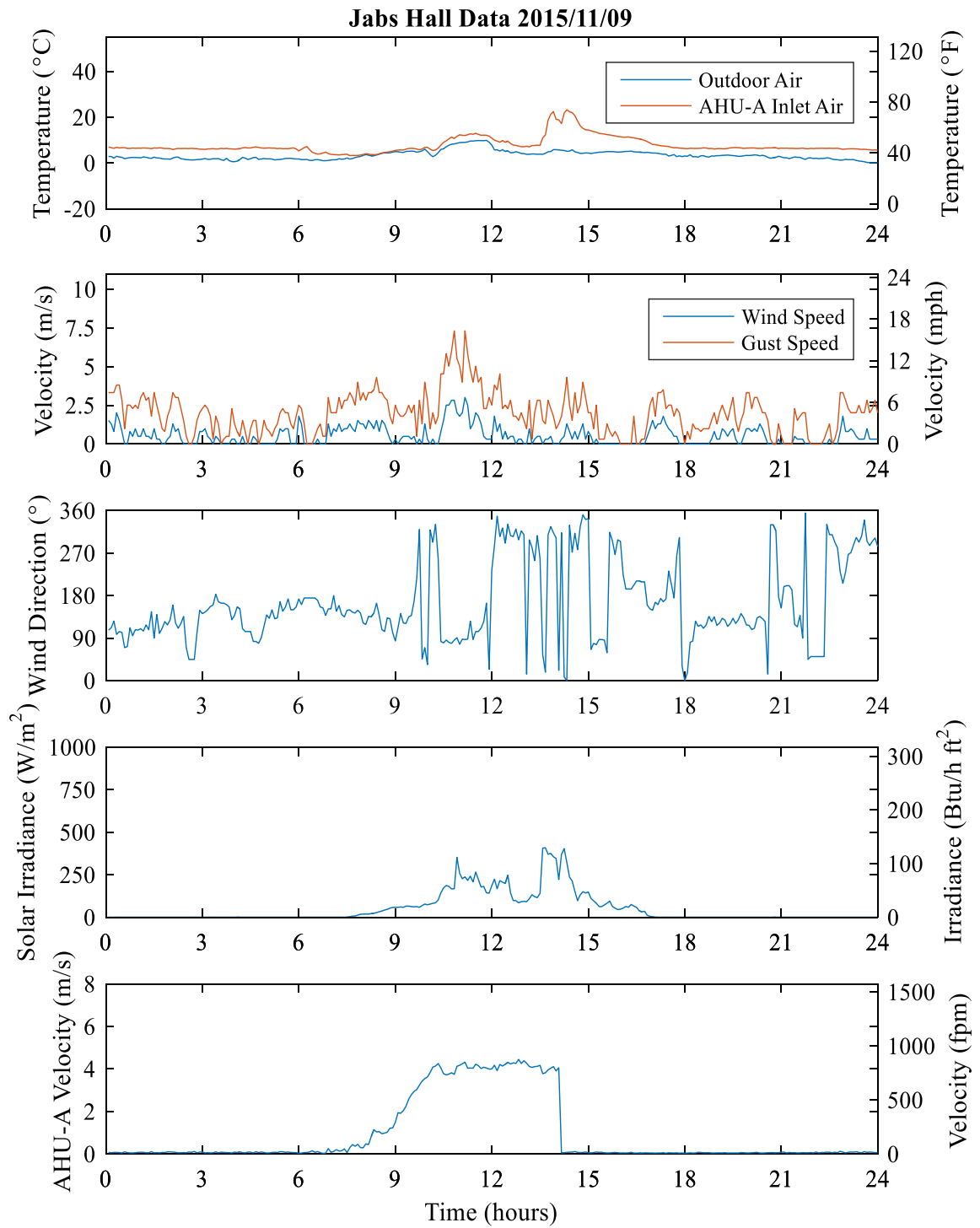


Figure 131: Jabs Hall Raw Data 2015/11/09

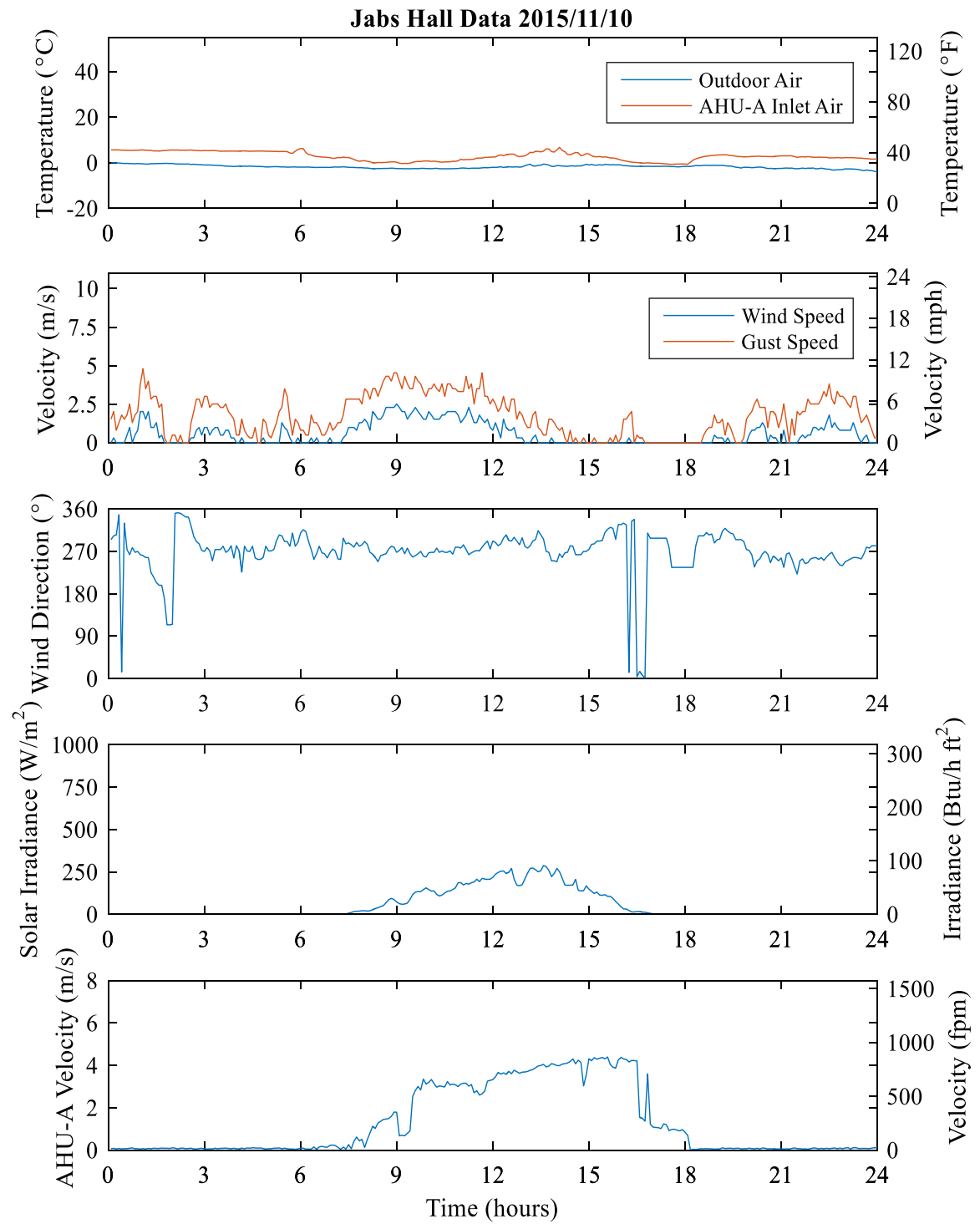


Figure 132: Jabs Hall Raw Data 2015/11/10

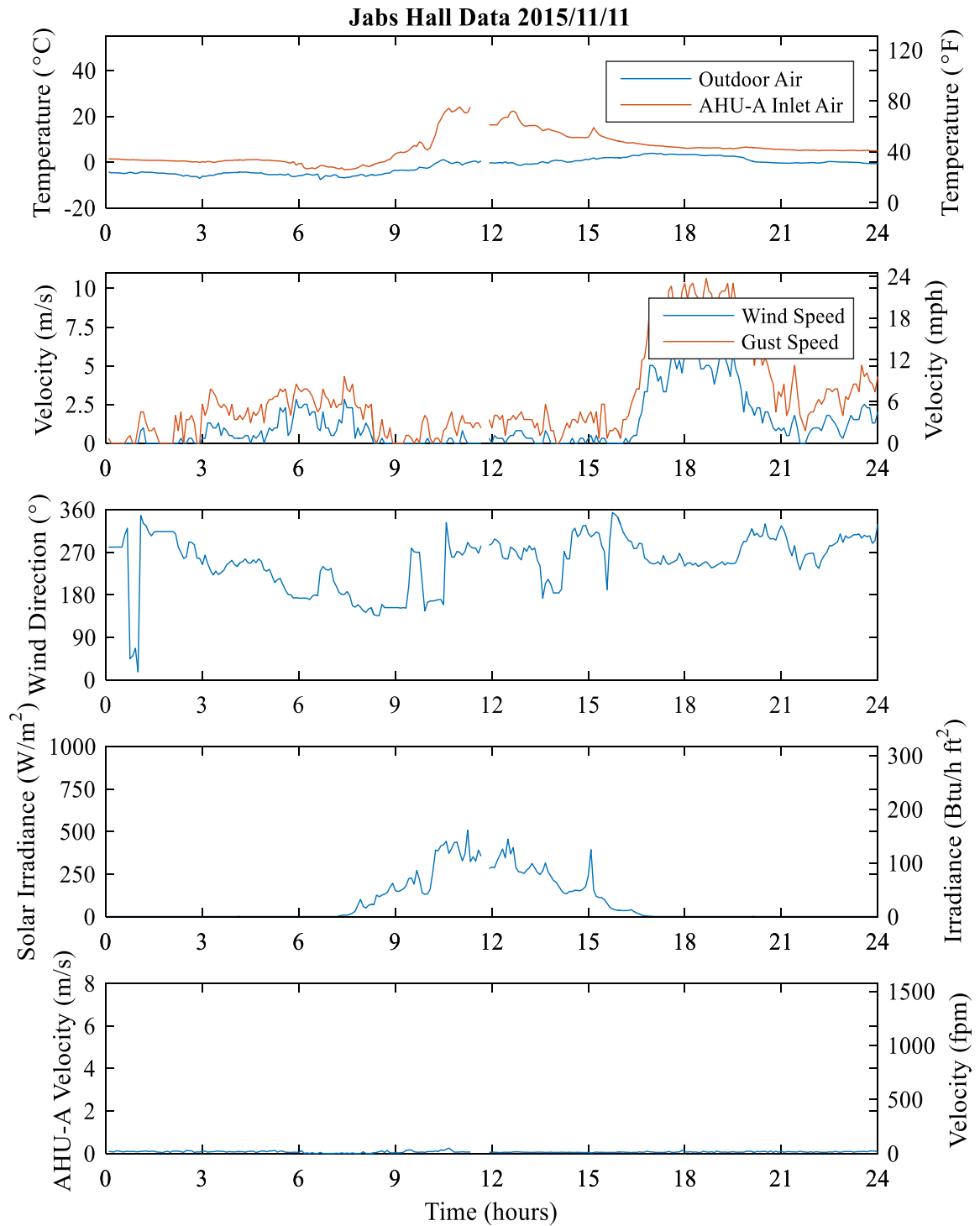


Figure 133: Jabs Hall Raw Data 2015/11/11

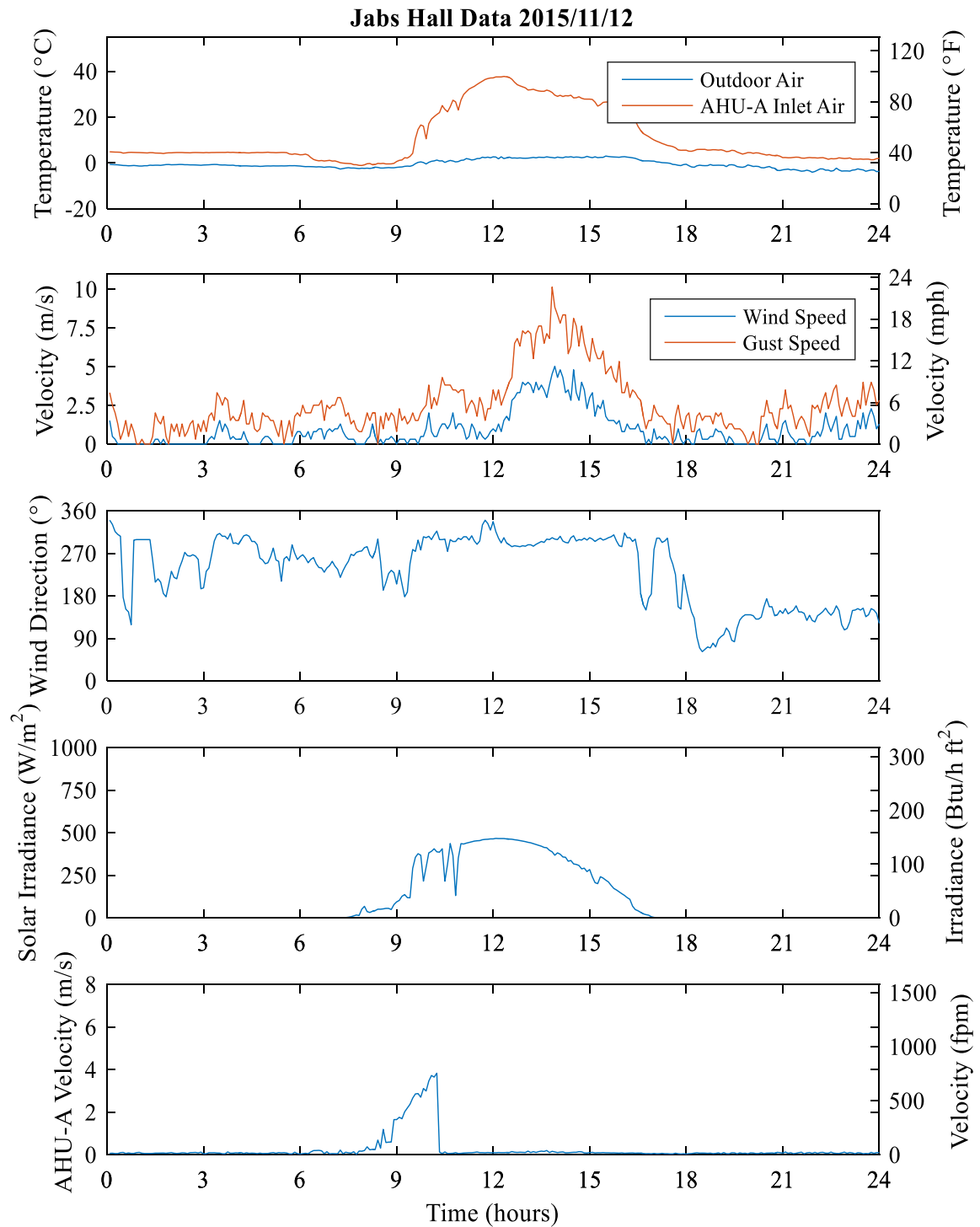


Figure 134: Jabs Hall Raw Data 2015/11/12

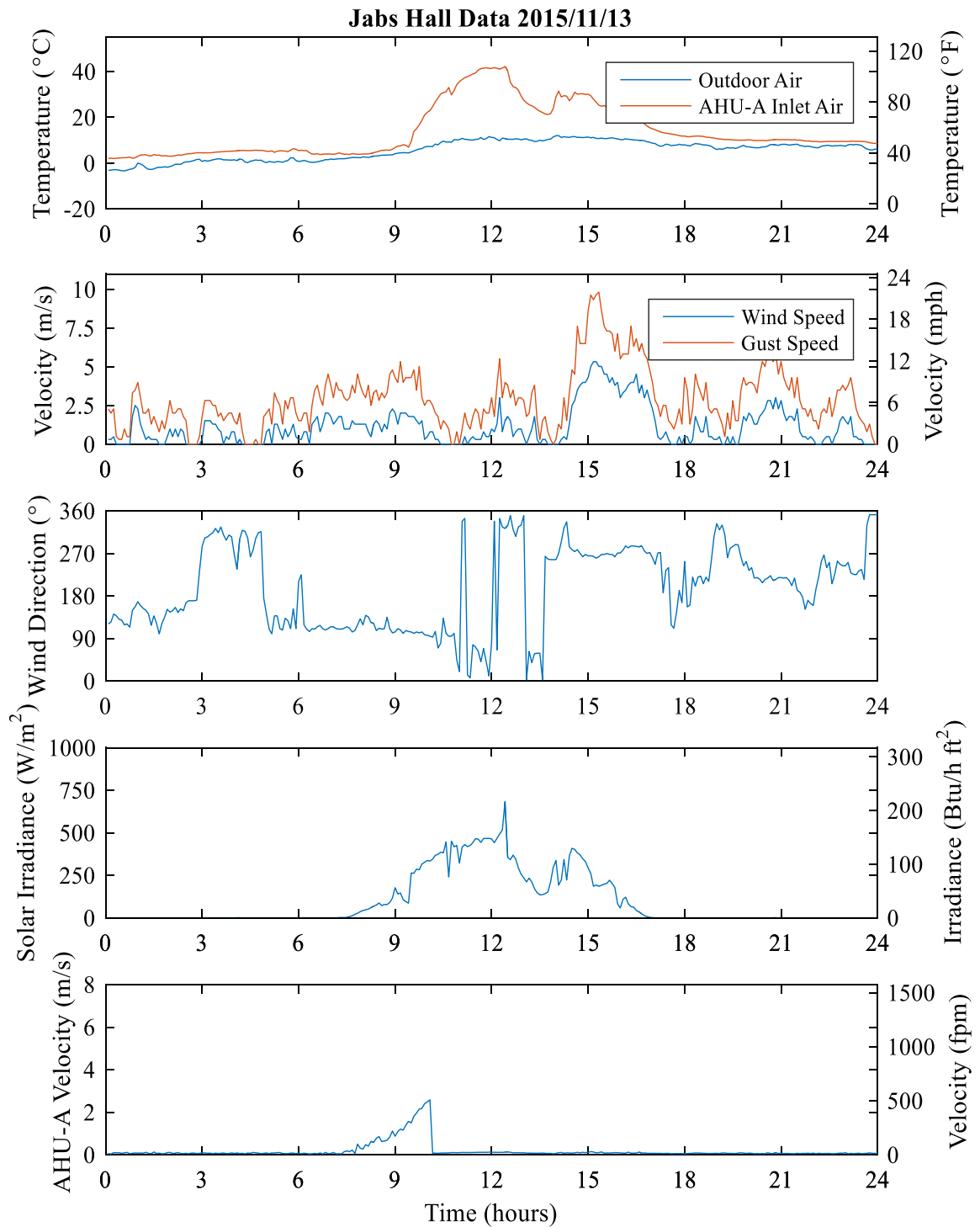


Figure 135: Jabs Hall Raw Data 2015/11/13

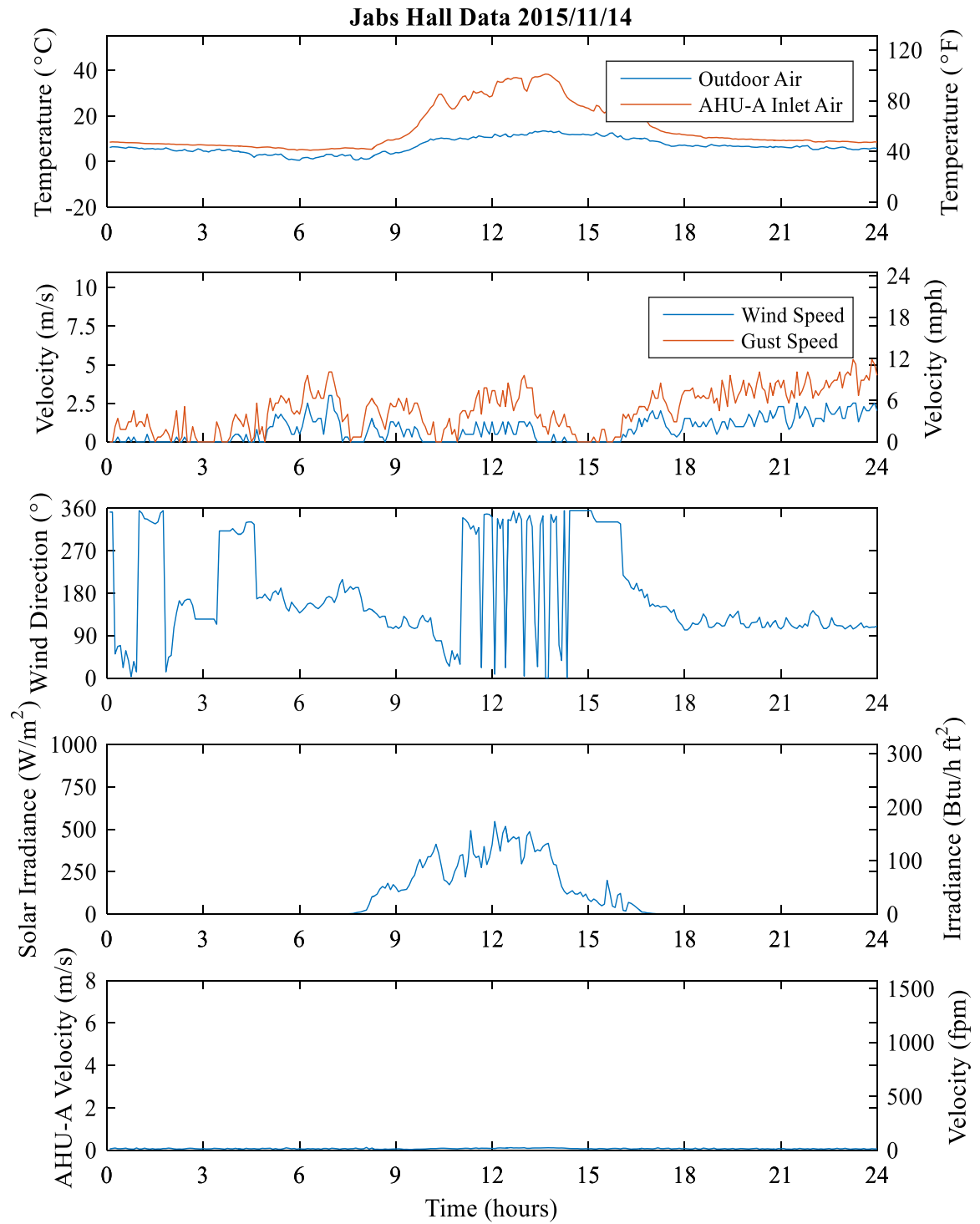


Figure 136: Jabs Hall Raw Data 2015/11/14

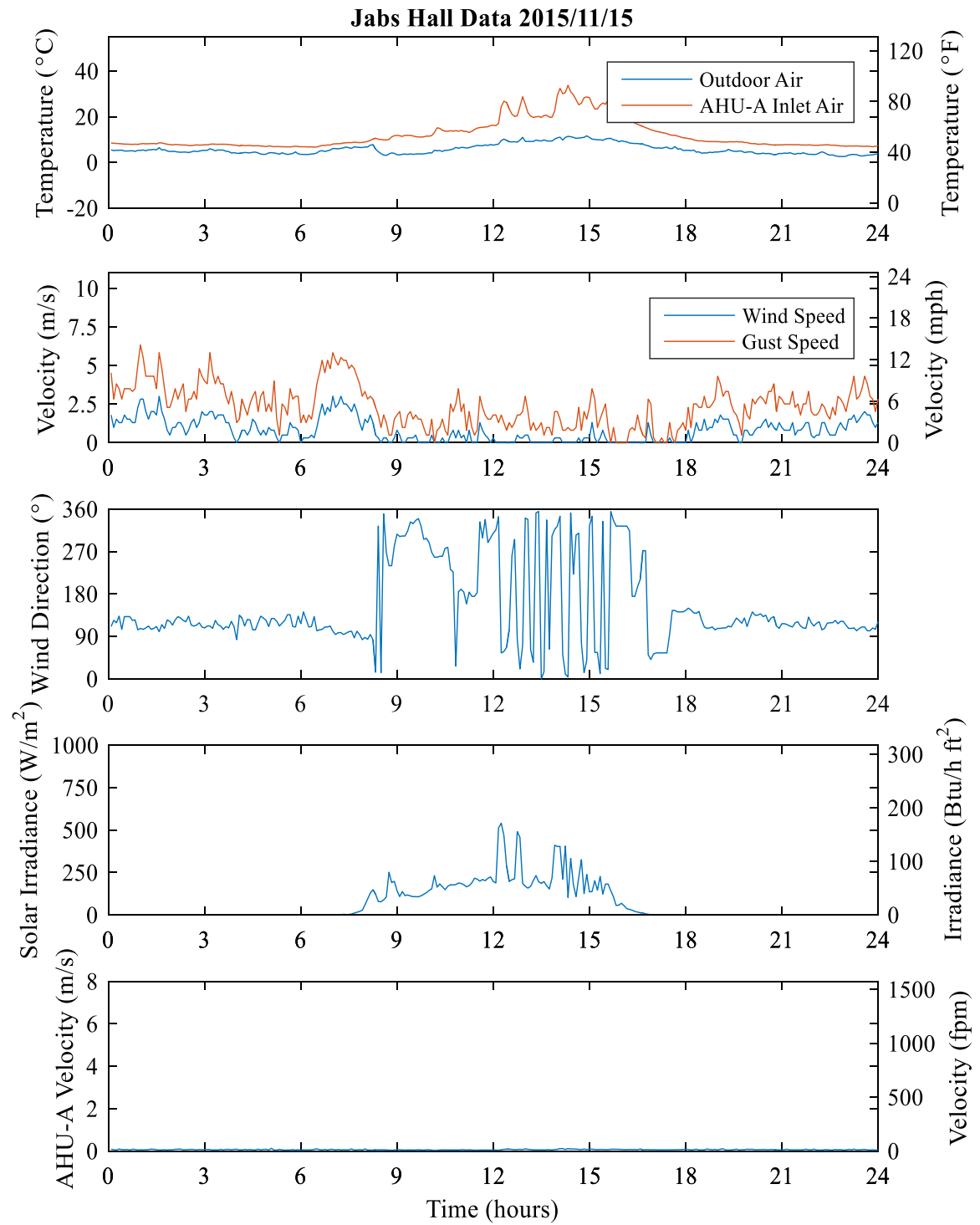


Figure 137: Jabs Hall Raw Data 2015/11/15

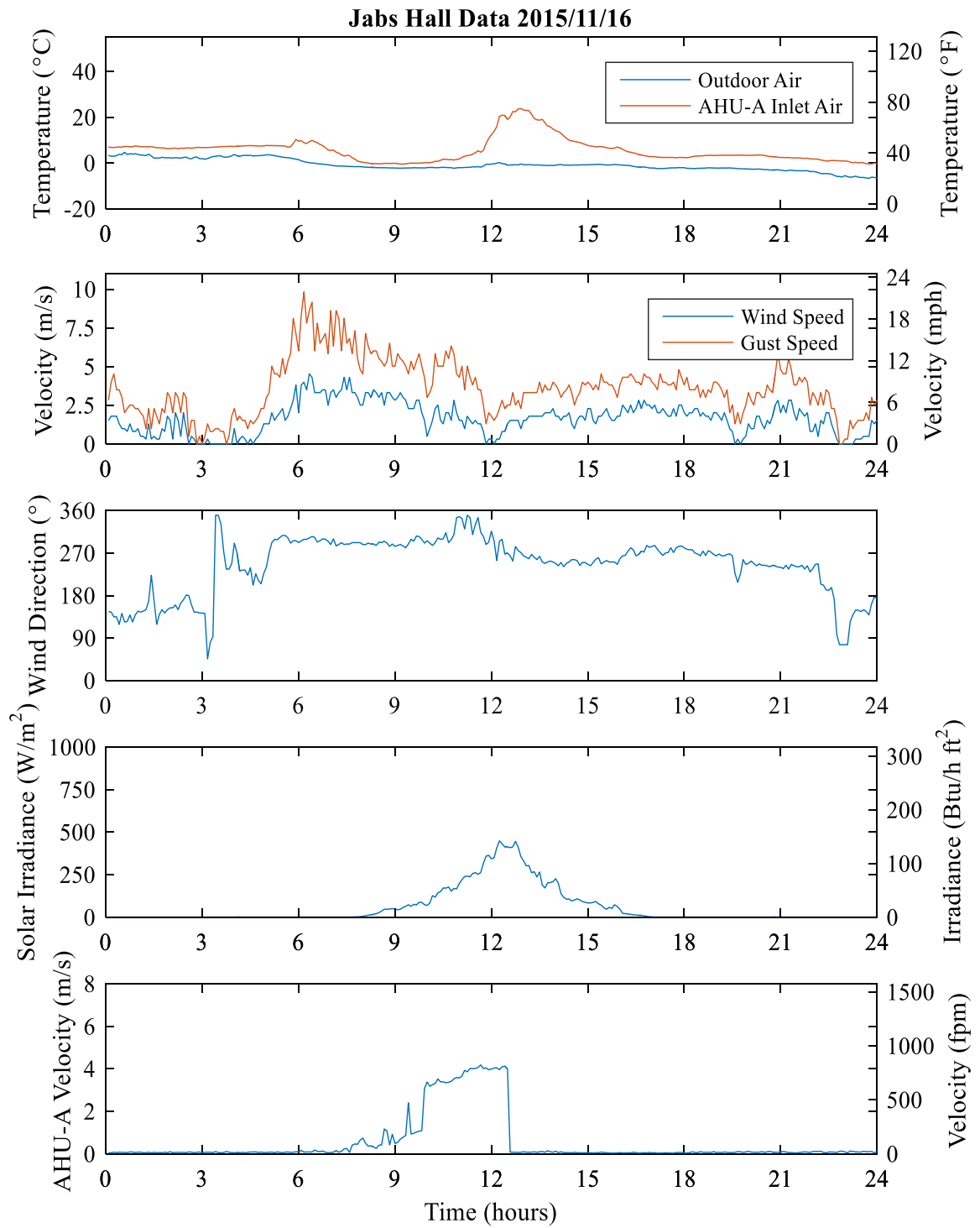


Figure 138: Jabs Hall Raw Data 2015/11/16

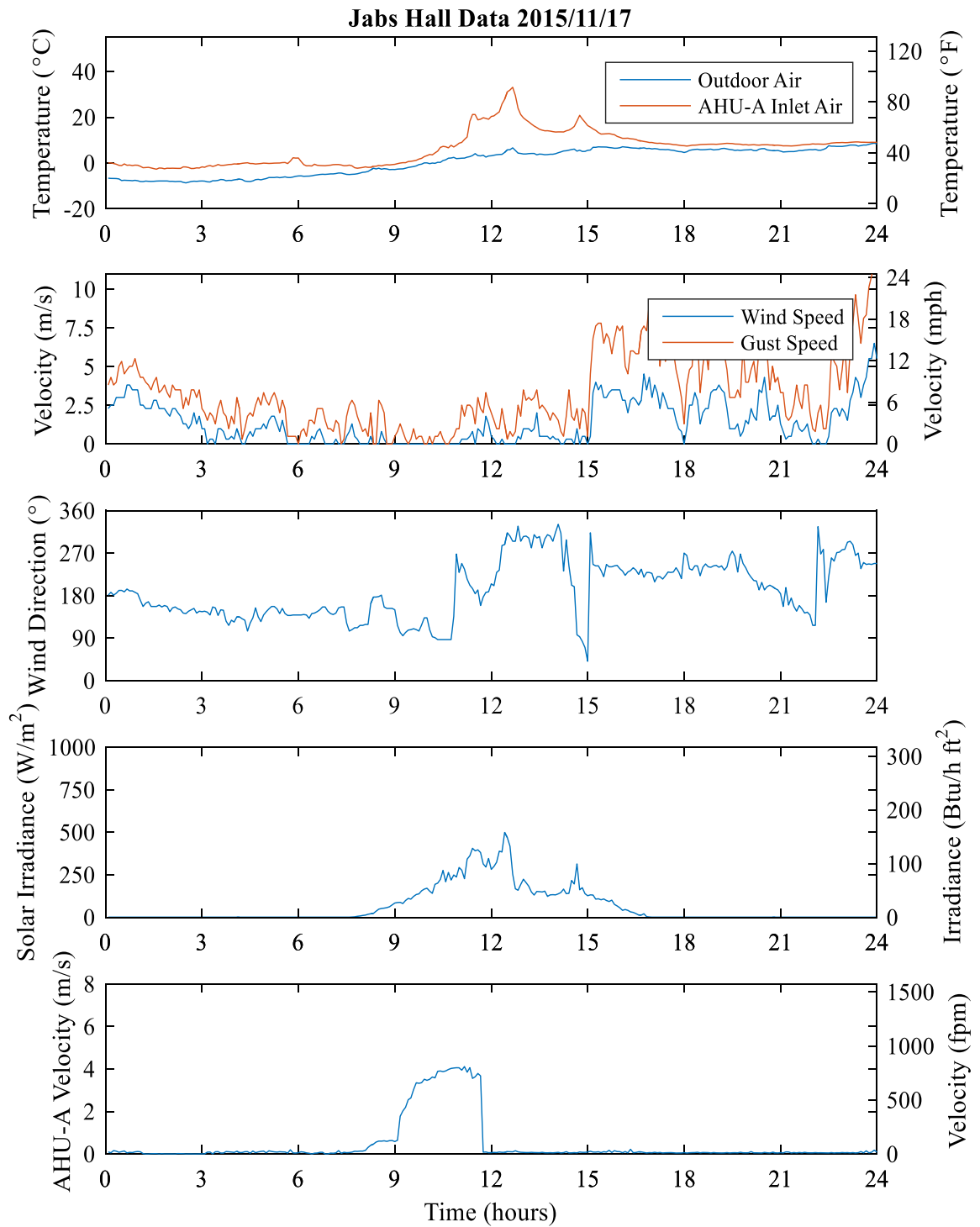


Figure 139: Jabs Hall Raw Data 2015/11/17

APPENDIX E

DATA ACQUISITION SPECIFICATION SHEETS



HOBOnet® U30 Remote Monitoring Systems

Real-time access to data from any web browser

This rugged weather station is one of Onset's most durable outdoor environmental monitoring solutions. Users can easily configure the HOBOnet U30-NRC Weather Station to fit their application needs. Use up to 15 channels to collect environmental data and then upload to HOBOnetware Pro software for expert analysis.

Supported Measurements: Barometric Pressure, Leaf Wetness, Light Intensity, PAR, Pulse Input, Rainfall, Relative Humidity, Soil Moisture, Solar Radiation, Temperature, Wind Speed & Direction, 4-20mA, Voltage Input

Key Advantages:

- Rugged double-weatherproof, tamper-proof enclosure
- Setup is quick and easy with plug-and-play sensors
- Fast data offload via USB
- Optional analog inputs with sensor excitation
- Includes relay that can be activated on user-defined alarm conditions



Minimum System Requirements:



¹AC power adapter or solar panel required. For more details, please visit onsetcomp.com.

Figure 140: HOBOnet® U30 Data Logger Manual, Page 1 of 2 [27]

► For complete information and accessories, please visit: www.onsetcomp.com

Part number	U30-NRC
Smart-Sensor Inputs	5 or 10
Data Channels	Maximum of 15 (some sensors use more than one data channel)
Smart Sensor Cable Length	100m (323ft) maximum
Alarm Relay	Can be activated, deactivated or pulsed on user-defined sensor alarms.
Logging Interval	1 minute to 18 hours, user-specified
Data Storage Memory	512K bytes local storage in non-volatile flash memory
Environmental Rating	Weatherproof enclosure, NEMA 4x
Operating Range	-40 to 60°C (-40 to 140°F) see battery life
Power	An Onset solar panel (1.2w, 3w, 6w) or AC adapter is required
Battery Life	3-5 years, 4 volt 10 AHr rechargeable sealed lead acid
Dimensions	17.8 x 11.7 x 19.3 cm (7.0 x 4.6 x 7.6 in)
Weight	2kg (4lbs 10oz)
Local Communication	USB
CE Compliant	Yes

Contact Us

Sales (8am to 5pm ET, Monday through Friday)

► Email sales@onsetcomp.com

► Call 1-508-759-9500

► In U.S. toll free 1-800-564-4377

► Fax 1-508-759-9100

Technical Support (8am to 8pm ET, Monday through Friday)

► Contact Product Support onsetcomp.com/support/contact

► Call 1-508-759-9500

► In U.S. toll free 1-877-564-4377

Onset Computer Corporation
470 MacArthur Boulevard
Bourne, MA 02532

Figure 141: HOB0® U30 Data Logger Manual, Page 1 of 2 [27]

Silicon Pyranometer Smart Sensor (S-LIB-M003) Manual



The silicon pyranometer smart sensor is designed to work with HOBO® stations. The smart sensor has a plug-in modular connector that allows it to be added easily to a station. All calibration parameters are stored inside the smart sensor, which automatically communicates configuration information to the logger without any programming, calibration, or extensive user setup.

Specifications

Measurement Range	0 to 1280 W/m ²
Spectral Range	300 to 1100 nm (see Plot A)
Accuracy	Typically within ±10 W/m ² or ±5%, whichever is greater in sunlight; Additional temperature induced error ±0.38 W/m ² /°C from 25°C (0.21 W/m ² /°F from 77°F)
Angular Accuracy	Cosine corrected 0 to 80 degrees from vertical (see Plot B); Azimuth Error < ±2% error at 45 degrees from vertical, 360 degree rotation
Resolution	1.25 W/m ²
Drift	< ±2% per year
Calibration	Factory recalibration available
Operating Temperature Range	-40° to 75°C (-40° to 167°F)
Environmental Rating	Weatherproof
Housing	Anodized aluminum housing with acrylic diffuser and O-ring seal
Dimensions	4.1 cm height x 3.2 cm diameter (1 5/8 in. x 1 1/4 in.)
Weight	120 g (4 oz)
Bits per Sample	10
Number of Data Channels*	1
Measurement Averaging Option	Yes
Cable Length Available	3.0 m (9.8 ft)
Length of Smart Sensor Network Cable*	3.0 m (9.8 ft)

 The CE Marking identifies this product as complying with all relevant directives in the European Union (EU).

* A single HOBO station can accommodate 15 data channels and up to 100 m (328 ft) of smart sensor cable (the digital communications portion of the sensor cables).

Silicon Pyranometer Smart Sensor

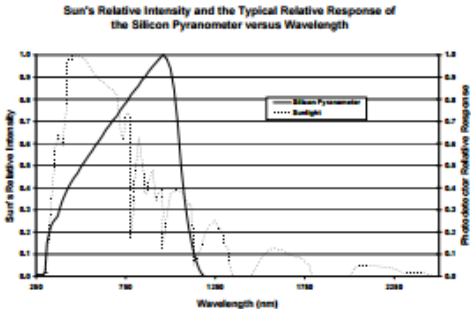
S-LIB-M003

Accessories:

- Light sensor mounting bracket (M-LBB)
- Light sensor level (M-LLA)

Spectral Characteristics

This sensor uses a silicon photodiode to measure solar power per unit area (watts per square meter). Silicon photodiodes are not ideal for use as solar radiation sensors and the photodiode in this silicon pyranometer is no exception (see Plot A). An ideal pyranometer has equal spectral response from 280 to 2800 nm. However, when calibrated properly and used correctly, the silicon pyranometer smart sensor should perform well in most situations.



Plot A: S-LIB-M003 Silicon Pyranometer Response Curve

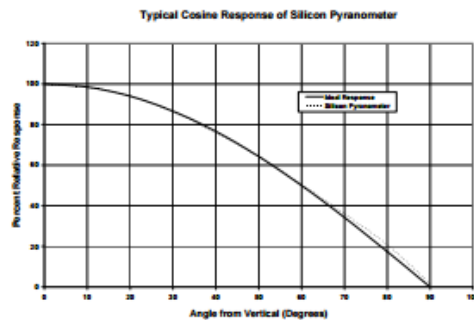
Figure 142: Silicon Pyranometer Smart Sensor (S-LIB-M003) Manual Page 1 of 3 [27]

The sensor is calibrated for use in sunlight (an Eppley Precision Spectral Pyranometer is used as reference standard). Accordingly, if the sensor is used under natural sunlight, the measurement errors will be small. Note that significant errors may result from using the sensor under artificial light, within plant canopies, in greenhouses, or any other conditions where the spectral content differs from sunlight.

Cosine Correction

The silicon pyranometer smart sensor housing is designed to give an accurate cosine response. Plot B shows a plot of relative intensity versus angle of incidence for a typical sensor and for the theoretical ideal response. Deviation from ideal response is less than 5% from 0 to 70 degrees and less than 10% from 70 to 80 degrees.

Note that as the angle approaches 90 degrees, the ideal cosine response approaches zero. As a result, small errors in measured intensity will result in very large percentage errors compared to the ideal response from 80 to 90 degrees.



Plot B: S-LIB-M003 Typical Cosine Response Curve

Mounting

Bracket Mounting

It is recommended that you mount the silicon pyranometer smart sensor with the light sensor bracket (M-LBB) on a pole or tripod. To mount the sensor using the bracket:

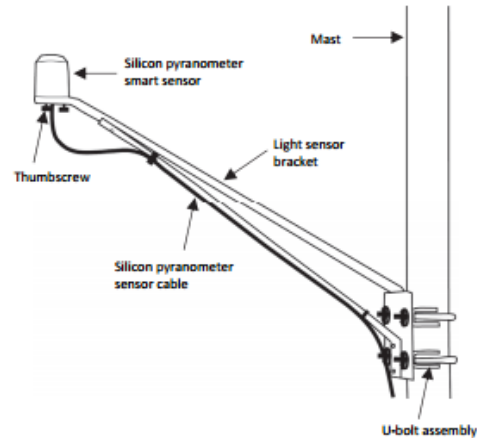
1. Attach the light sensor bracket to a 1½ inch - 1⅝ inch pole with the provided U-bolts.

Note: The bracket can also be mounted on a flat, vertical surface using four screws.

2. Position the silicon pyranometer sensor on top of the bracket with its cable running through the slot in the bracket.
3. Using the two screws supplied, attach the sensor to the bracket through the two holes on either side of the slot.

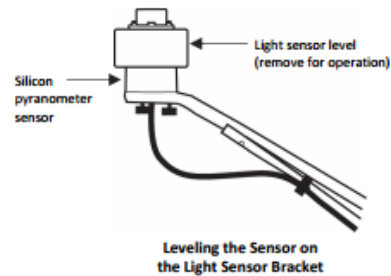
Note: Do not completely tighten the screws until you level the sensor.
4. Position the bracket so it faces toward the equator, minimizing the chance of shading.
5. Mount the bracket on the mast with the two U-bolt assemblies, mounting it high enough on the mast to avoid the possibility of shading the sensor.

Note: If you mount the sensor above eye level, it is recommended that you use a step ladder or other secure platform when leveling the sensor so that you can clearly view the light sensor level (M-LLA).



Silicon Pyranometer Sensor Bracket Mounting

6. Make sure the screws holding the sensor to the mounting bracket are loose.
7. Place the light sensor level on the silicon pyranometer smart sensor.
8. Adjust the height of the thumbscrews to level the sensor (start with the thumbscrews protruding about 1/16 inch from the bracket).
9. Once the sensor is near level, tighten the Phillips head screws.
10. Check the level and repeat above steps if necessary.
11. **IMPORTANT:** Don't forget to remove the level when you are done with it.

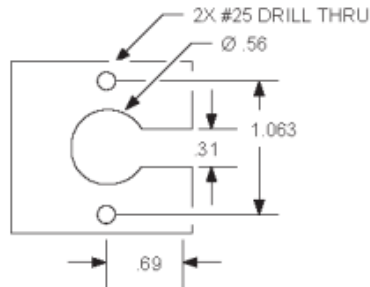


Specialized Application Mounting

To mount the silicon pyranometer sensor using a mounting plate of your own design:

1. Drill a 0.56 (9/16) inch hole in the middle of the plate, then drill two #25 holes 1.063 (1-1/16) inches apart on either side of the center hole. Cut a 0.31 (5/16) inch-wide slot in the mounting plate. See diagram on next page. The plate should be a thickness of 1/8 inch or less.
2. Slide the sensor through the 0.31 (5/16) inch-wide slot.

3. Attach the sensor using two 6-32 x 3/8 inch screws and lock washers (not included).
4. Shim the sensor as necessary to level it.



Recommended Mounting Plate Dimensions

Mounting Considerations

- Small errors in alignment can produce significant errors. Be certain that the sensor is mounted level.
- Mount the sensor where it will not be in a shadow. Any obstruction should be below the plane of the sensor head. If that is not possible, try to limit obstructions to below 5 degrees, where the effect will be minimal.
- If possible, avoid locating the sensors in dusty locations. Dust, pollen, and salt residue that collect on the top of the sensor can significantly degrade accuracy.
- Refer to the station manual and Tripod Setup Guide for more information regarding setting up stations.

Connecting the Smart Sensor to a Station

To connect the sensor to a station, stop the station from logging and insert the smart sensor's modular jack into an available smart sensor port on the station. See the station manual for details on operating stations with smart sensors.

Operation

The silicon pyranometer smart sensor supports measurement averaging. When measurement averaging is enabled, data is sampled more frequently than it is logged. The multiple samples are then averaged together and the average value is stored as the data for the interval. For example, if the logging interval is set at 10 minutes and the sampling interval is set at 1 minute, each recorded data point will be the average of 10 measurements.

Measurement averaging is useful for reducing noise in the data. It is recommended that you use measurement averaging whenever the silicon pyranometer smart sensor is placed in an area where the light level can vary quickly with respect to the logging interval (for example, during partly cloudy conditions). Note that fast sampling intervals less than 1 minute may significantly reduce battery life. See the station manual for more details about battery life.

Maintenance

Dust on the sensor will degrade sensor accuracy. Periodically inspect the sensor, and if necessary, gently clean the diffuser with a damp sponge. Do not open the sensor as there are no user serviceable parts inside.

Warning: DO NOT use alcohol, organic solvents, abrasives, or strong detergents to clean the diffuser element on the silicon pyranometer smart sensor. The acrylic material used in the sensors can be crazed by exposure to alcohol or organic solvents. Clean the sensor only with water and/or a mild detergent such as dishwashing soap if necessary. It is recommended that you use vinegar to remove hard water deposits from the diffuser element. Under no circumstances should the smart sensor be immersed in any liquid.

Verifying Sensor Accuracy

It is recommended that you test the silicon pyranometer smart sensor annually for accuracy. If the sensor is not providing accurate data, it may be damaged or out of calibration. If you are unsure of accuracy, send the smart sensor back to Onset for testing and possible re-calibration. Only Onset can complete calibration. Contact Onset or your dealer for a Return Merchandise Authorization (RMA) number before sending the sensor.

Wind Speed Smart Sensor (S-WSA-M003) Manual



Wind Speed Smart Sensor
S-WSA-M003

Item included:

- Mounting rod

Accessories:

- Full cross arm (M-CAA)
- Half cross arm (M-CAB)

The wind speed smart sensor is designed to work with HOBO® stations. The smart sensor has a plug-in modular connector that allows it to be added easily to a HOBO station. All sensor parameters are stored inside the smart sensor, which automatically communicates configuration information to the logger without the need for any programming or extensive user setup.

Specifications

Measurement Range	0 to 45 m/sec (0 to 100 mph)
Accuracy	±1.1 m/sec (2.4 mph) or ±4% of reading, whichever is greater
Resolution	0.38 m/sec (0.8 mph)
Service Life	>5 year life typical, factory replaceable mechanism
Distance Constant	3 m (9.8 ft)
Starting Threshold	≤1 m/sec (2.2 mph)
Maximum Wind Speed Survival	54 m/sec (120 mph)
Measurements	Wind speed: Average wind speed over logging interval Gust: Highest 3-second gust during the logging interval See Measurement Operation for more information.
Operating Temperature Range	-40° to 75°C (-40° to 167°F)
Environmental Rating	Sensor and Cable Jacket: Weatherproof
Housing	Three cup polycarbonate anemometer; Modified Teflon® bearings and hardened beryllium shaft with ice shedding design
Dimensions	41 x 16 cm (16 x 6.5 in.) including 1.27 cm (0.5 in) diameter mounting rod; 5.5 cm (2.1 in.) drip overhang
Weight	300 g (10 oz)
Bits per Sample	8 for each channel, 16 total
Number of Data Channels*	2
Measurement Averaging	No
Cable Length Available	3.5 m (11.5 ft)
Length of Smart Sensor Network Cable*	0.5 m (1.6 ft)

CE The CE Marking identifies this product as complying with all relevant directives in the European Union (EU).

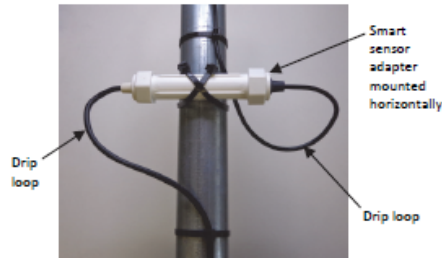
* A single HOBO station can accommodate 15 data channels and up to 100 m (328 ft) of smart sensor cable (the digital communications portion of the sensor cables).

Figure 145: Wind Speed Smart Senor (S-WSA-M003) Manual Page 1 of 3 [27]

Mounting

Placement and Mounting Considerations

- The wind speed smart sensor should be mounted vertically in a location free of wind shadows.
- For accurate wind speed measurements, mount the sensor at a distance of at least five times the height of the nearest tree, building, or other obstruction.
- Be sure to secure the sensor cable with cable ties to protect the cable from damage.
- To provide long-term protection from moisture entry, the smart sensor adapter must be mounted horizontally and with the cable wires routed with drip loops so that water drains away from the cable entry point as shown in the example below. When mounted properly, the housing is weatherproof (but not waterproof).

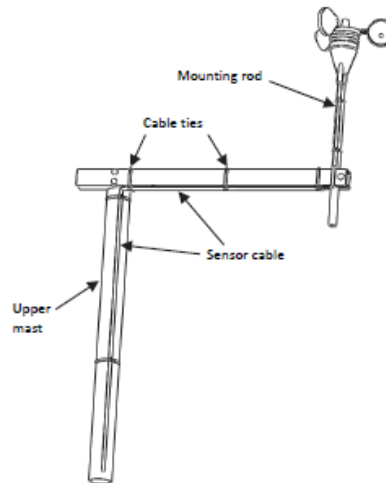


- The tripod or mounting mast must be properly grounded. For field installations, you can use Onset's grounding kit (M-GKA).
- Secure the mast the wind sensor is mounted on so that it does not vibrate. If you are using Onset masts or tripods, secure them with guy wires.
- Although the wind sensor is designed to operate in 100+ mph winds, it can be damaged with improper handling. Store the sensor in its shipping box until you are ready to install it.
- Refer to the Tripod Setup Guide for more information.

Mounting the Sensor to a Tripod Cross Arm

1. Insert a 1/4-20 x 1-3/4 inch hex head bolt with a flat washer on it through the 1/4 inch hole on the end of the cross arm. Tighten with a 7/16 inch wrench until snug.
2. Install another flat washer and nylock nut on the bolt, allowing the black mounting rod to protrude 1/2 inch (1.3 cm) from the bottom of the cross arm.
3. Insert the sensor mounting rod into the cross arm. Secure the ground wire to the lug nut on the cross arm.
4. Tighten the nut and bolt until the rod is clamped in place.
5. Adjust the height of the sensor in the cross arm as necessary using one of the following methods and then tighten the nut and bolt until the cross arm just starts to deform.

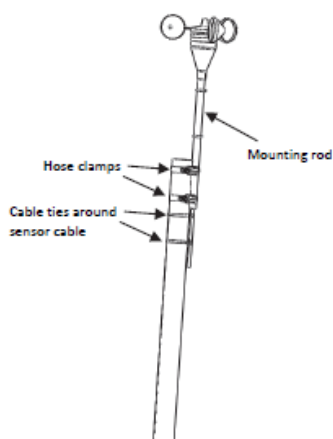
- a. Loosen the tri-clamp bolts and raise or lower the entire mast so that the wind sensor is close to the desired height. Make sure there is at least 5 cm (2 inches) of mast extending below the lower tri-clamp.
 - b. Make sure the upper mast dimple is still facing north (if in northern hemisphere) and then re-tighten the tri-clamps. Once the tri-clamp bolts are tight, tighten the lock nuts to lock the bolts in place. This requires two wrenches: one to hold the bolt and one to tighten the lock nut against the tri-clamp.
 - c. Loosen the bolt holding the wind sensor mounting rod and raise or lower it as necessary so the center of the wind sensor anemometer cups is at the desired height. Re-tighten the bolt.
6. Use cable ties to secure the sensor cables to the cross arm, bracket, and mast. The sensor cables should run below the cross arm and brackets to minimize the chance of birds pecking and damaging the cables. Cable ties should be spaced no more than .3 m (1 foot) apart. Make sure there are drip loops on both sides of the smart sensor housing, which must also be mounted horizontally, as described under *Placement and Mounting Considerations*.



Mounting the Sensor to a Pole

1. Loosely secure the sensor mounting pole with two hose clamps (not included) as shown below. Adjust the height of the sensor as necessary, but make sure the hose clamps are separated by at least 4 inches (10 cm).
2. Secure the sensor cable with cable ties. See diagram on next page. Make sure there are drip loops on both sides of the smart sensor housing, which must also be mounted horizontally, as described under *Placement and Mounting Considerations*.

Figure 146: Wind Speed Smart Sensor (S-WSA-M003) Manual Page 2 of 3 [27]



3. Tighten the hose clamps making sure the mounting rod remains vertical.

Connecting the Sensor to a Station

To connect the sensor to a station, stop the station from logging and insert the smart sensor's modular jack into an available smart sensor port on the station. See the station manual for details on operating stations with smart sensors.

Measurement Operation

Wind speed measurements are averaged over the logging interval or a 3-second timeframe (whichever is greater). If you set up the sensor to log faster than every 3 seconds, the same sensor reading will be recorded until a new 3-second average is calculated. For example, if the sensor is logging at a 1-second interval, the sensor will report the same wind speed (its calculated average) for three samples before calculating and reporting a new value for another three samples. Gust speed is the highest three-second wind recorded during the logging interval.

Maintenance

The sensor does not require any maintenance other than an occasional cleaning. If dust, cobwebs, salt or other contaminants collect in the cups of the anemometer, rinse the sensor with mild soap and fresh water.

Verifying Sensor Accuracy

Onset recommends that you check the accuracy of the sensor annually. The Wind Speed smart sensor cannot be calibrated. Onset uses precision components to obtain accurate measurements. If the smart sensor is not providing accurate data, then it may be damaged or possibly worn out if it has been in use for several years. If you are unsure of the smart sensor's accuracy, you can send the smart sensor back to Onset for re-certification and replacement of the mechanism if needed. Contact Onset or your dealer for a Return Merchandise Authorization (RMA) number before sending the sensor.

Wind Direction Smart Sensor (S-WDA-M003) Manual



Wind Direction
Smart Sensor

S-WDA-M003

Item included:

- Mounting rod

Accessories:

- Full cross arm (M-CAA)
- Half cross arm (M-CAB)

The Wind Direction smart sensor is designed to work with HOBO® stations. The smart sensor has a plug-in modular connector that allows it to be added easily to a HOBO station. All sensor parameters are stored inside the smart sensor, which automatically communicates configuration information to the logger without the need for any programming or extensive setup.

Specifications

Measurement Range	0 to 355 degrees, 5 degree dead band
Accuracy	±5 degrees
Resolution	1.4 degrees
Starting Threshold	1 m/s (2.2 mph)
Maximum Wind Speed Survival	67 m/s (150 mph)
Measurement Definition	Unit vector averaging used; vector components for each wind measurement are calculated every three seconds for duration of logging interval (see <i>Measurement Operation</i>)
Operating Temperature Range	-40°C to 70°C (-40°F to 158°F)
Environmental Rating	Weatherproof
Service Life	4 to 6 years typical depending upon environmental conditions
Housing	Injection-molded plastic housing and vane, static dissipating base, lead-free silicon bronze nose and aluminum mounting rod
Bearing Type	Two shielded stainless steel ball bearing
Turning Radius	Approximately 13.5 cm (5.25 in.)
Dimensions	46 x 20 cm (18 x 8.5 in.) including 1.27 cm (0.5 in) diameter mounting rod; 2.5 mm (0.1 in.) drip overhang
Weight	370 g (13 oz)
Bits per Sample	8
Number of Data Channels*	1
Measurement Averaging Option	Automatic averaging (see <i>Measurement Operation</i>)
Cable Length Available	3.5 m (11.5 ft)
Length of Smart Sensor	0.5 m (1.6 ft)
Network Cable*	



The CE Marking identifies this product as complying with all relevant directives in the European Union (EU).

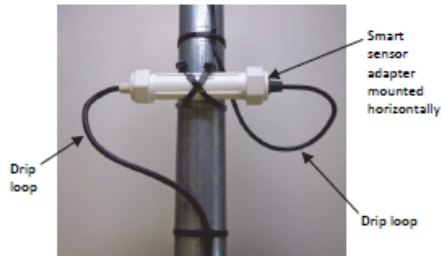
* A single HOBO station can accommodate 15 data channels and up to 100 m (328 ft) of smart sensor cable (the digital communications portion of the sensor cables).

Figure 148: Wind Direction Smart Senor (S-WDA-M003) Manual Page 1 of 4 [27]

Mounting

Placement and Mounting Considerations

- The Wind Direction smart sensor should be mounted vertically in a location free of wind shadows.
- For accurate wind direction measurements, mount the sensor at a distance of at least five times the height of the nearest tree, building, or other obstruction.
- Be sure to secure the sensor cable with cable ties to protect it from damage.
- The tripod or mounting mast must be properly grounded. For field installations, you can use Onset's Grounding Kit (M-GKA).
- Secure the mast the wind sensor is mounted on so that it does not vibrate. If you are using Onset masts or tripods, secure them with guy wires.
- The sensor can be damaged with improper handling. Store the sensor in its shipping box until you are ready to install it.
- To minimize measurement errors due to ambient RF, use the shortest possible probe cable length and keep the probe cable as far as possible from other cables carrying high frequency or high-current signals.
- To provide long-term protection from moisture entry, the smart sensor adapter must be mounted horizontally and with the cable wires routed with drip loops so that water drains away from the cable entry point as shown in the example below. When mounted properly, the housing is weatherproof (but not waterproof).

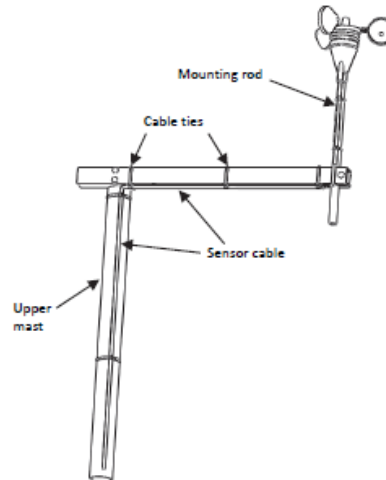


- Refer to the Tripod Setup Guide for more information.

Mounting the Sensor to a Tripod Cross Arm

1. Insert a 1/4-20 x 1 3/4 inch hex head bolt with a flat washer on it through the 1/4 inch hole on the end of the cross arm. Install a lock washer and nut on the bolt. Tighten with a 7/16 inch wrench until snug.
2. Insert the sensor mounting rod into the cross arm allowing the mounting rod to protrude 1.3 cm (1/2 inch) from the bottom of the cross arm.
3. Tighten the nut and bolt until the rod is slightly clamped in place.

4. Adjust the height of the sensor in the cross arm as necessary using one of the following methods and then tighten the nut and bolt until the cross arm just starts to deform.
 - a. Loosen the tri-clamp bolts and raise or lower the entire mast so the sensor is close to the desired height. Make sure there is at least 5 cm (2 inches) of mast extending below the lower tri-clamp.
 - b. Make sure the upper mast dimple is still facing north (if in northern hemisphere) and then re-tighten the tri-clamps. Once the tri-clamp bolts are tight, tighten the lock nuts to lock the bolts in place. This requires two wrenches: one to hold the bolt and one to tighten the lock nut against the tri-clamp.
 - c. Loosen the bolt holding the sensor mounting rod and raise or lower it as necessary to the desired height. Re-tighten the bolt.
5. Use cable ties to secure the sensor cables to the cross arm, bracket, and mast. The sensor cables should run below the cross arm and brackets to minimize the chance of birds pecking and damaging the cables. Cable ties should be spaced no more than 0.3 m (1 foot) apart. Make sure there are drip loops on both sides of the smart sensor housing, which must also be mounted horizontally, as described under *Placement and Mounting Considerations*.

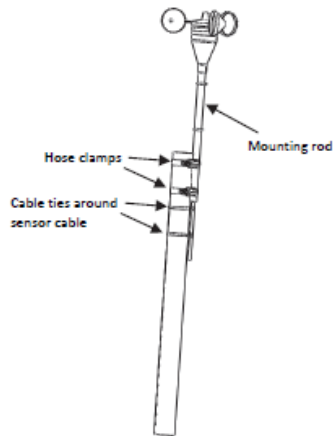


Mounting the Sensor to a Pole

1. Loosely secure the sensor with two hose clamps (not included). Adjust the height as necessary, but make sure the hose clamps are separated by at least 4 inches (10 cm).

Figure 149: Wind Direction Smart Sensor (S-WDA-M003) Manual Page 2 of 4 [27]

2. Secure the sensor cable with cable ties. Make sure there are drip loops on both sides of the smart sensor housing, which must also be mounted horizontally, as described under *Placement and Mounting Considerations*.



3. Tighten the hose clamps making sure the mounting rod remains vertical.
4. Follow the steps in the *North Alignment* section.

North Alignment

The wind direction sensor must be oriented properly to obtain meaningful data. This involves aligning the north markings on the base of the sensor with true north. There are two methods to align the sensor:

- Compass Alignment
- Global Positioning Satellite (GPS) alignment.

Note: The magnetic declination must be known to align the direction sensor to true north using a magnetic compass. Worldwide declination information is available from the National Space Science Data Center at: <http://nssdc.gsfc.nasa.gov/space/cgm/cgm.html>.

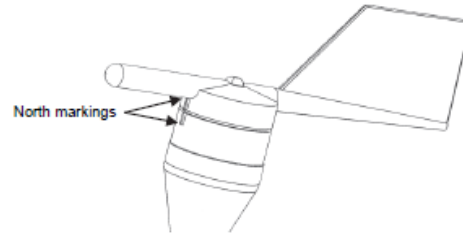
Compass Alignment

Tools required:

- Compass
- Binoculars
- Tape (such as electrical, packing, or duct tape)

Two people are required to complete this procedure.

1. Align bronze tip of the wind vane with the north markings on the base.



2. Secure the base and vane shaft with a piece of tape so that the vane cannot rotate.
3. While standing 150 to 200 feet south of the sensor, use the compass to determine magnetic north. If true north is the same as magnetic north, align yourself so the compass points north and directly at the sensor. If you are in area with an east variation, align yourself so that the station is that number of degrees to the east of magnetic north. If you are in an area with a west variation, align yourself so that the station is that number of degrees to the west of magnetic north.
4. While viewing the sensor through binoculars, instruct another person to rotate the sensor mounting rod to point the vane north. The vane should seem to disappear from sight when properly aligned.
5. Once you've obtained the correct position, secure the mounting rod and remove the tape.

GPS Alignment

Tools required:

- Handheld GPS with WAAS-enabled receiver or any similar high accuracy GPS device
- Flag, orange cone, or other temporary marker
- Laptop computer with logger software installed

This procedure requires only one person, but is easier to complete with two people. In this procedure, you will be using the GPS receiver first to create an arbitrary waypoint and then to determine the bearing from the sensor to that waypoint. You will then align the sensor so that when the vane is pointed at the waypoint, the direction reported by the logger software matches the GPS receiver's bearing to the waypoint.

1. Connect the sensor to the logger (refer to the *Connecting to the Logger* section below).
2. Connect the laptop to the logger with the PC interface cable.
3. Pick a visible location that is at least 100 meters (110 yards) away from the wind direction sensor and walk to it. Establish a waypoint with the handheld GPS receiver. You may want to use averaging to minimize the waypoint position error if your GPS receiver is so equipped. (For best results, the estimated position error of the waypoint should be less than 10 feet if the distance to the sensor is 100 meters, and less than 20 feet for a distance of 200 meters. Mark the waypoint with a flag, orange cone, or other suitable marker.

Figure 150: Wind Direction Smart Sensor (S-WDA-M003) Manual Page 3 of 4 [27]

4. Walk back to the sensor and determine the bearing to the waypoint you just created with the GPS receiver. Again you may need to determine the average value of the bearing to keep the errors to a minimum.
5. Start the logger software and select Status to get the current reading (refer to the software manual or online help for details about operating the software).
6. Point the sensor vane directly at the waypoint flag or marker and rotate the sensor mounting rod until the wind direction sensor value in the logger software matches the angle obtained with the GPS receiver.
7. Once the vane is in position, secure the mounting rod and then double-check that the reported angle is correct.

Connecting the Sensor to a Station

To connect the sensor to a station, stop the station from logging and insert the smart sensor's modular jack into an available smart sensor port on the station. See the station manual for details on operating stations with smart sensors.

Measurement Operation

Wind direction measurements are averaged over the logging interval or a 3-second timeframe (whichever is greater). If you set up the sensor to log faster than every 3 seconds, the same sensor reading will be recorded until a new 3-second average is calculated. For example, if the sensor is logging at a 1-second interval, the sensor will report the same wind direction (its calculated average) for three samples before calculating and reporting a new value for another three samples.

Direction Averaging

Unit vector averaging is used to determine wind direction because traditional averaging would produce inaccurate results. For example, three measurements of 350, 11, and 12 degrees—which are all winds from the north—averaged together would result in 126 degrees, which incorrectly indicates a southeasterly wind. Instead, the vector components (North/South and East/West) for each wind measurement are calculated every three seconds for the duration of the logging interval. At the conclusion of the logging interval, the North/South and East/West components are averaged and then re-combined to calculate the average wind direction for the logging interval.

Maintenance

The sensor does not normally require any maintenance other than an occasional cleaning. If the vane becomes dirty, rinse the sensor with mild soap and fresh water. Do not immerse the sensor in water or use any organic solvents to clean the unit.

Verifying Sensor Accuracy

It is recommended that you check the accuracy of the sensor annually. The wind direction sensor cannot be calibrated. Onset uses precision components to obtain accurate measurements. If the smart sensor is not providing accurate data, then it is damaged or possibly worn out if it has been in use for several years. If you are unsure of the accuracy, you can send the smart sensor back to Onset for inspection and possible replacement of the mechanism or bearings if required. Contact Onset or your dealer for a Return Merchandise Authorization (RMA) number before sending the sensor.

Figure 151: Wind Direction Smart Sensor (S-WDA-M003) Manual Page 4 of 4 [27]

Temperature/RH Smart Sensor (S-THB-M00x) Manual



Temperature/RH Smart Sensor

Models: S-THB-M002
S-THB-M008

Accessories:

- Solar radiation shield (M-RSA or RS3)
- Replacement RH sensor (HUM-RHPCB-2)

The temperature/RH smart sensor is designed to work with smart sensor-compatible HOBO® data loggers and stations. All sensor parameters are stored inside the smart sensor, which automatically communicates configuration information to the logger without any programming, calibration or extensive user setup.

Specifications

	Temperature	RH
Measurement Range	-40°C to 75°C (-40°F to 167°F)	0-100% RH at -40° to 75°C (-40° to 167°F); exposure to conditions below -20°C (-4°F) or above 95% RH may temporarily increase the maximum RH sensor error by an additional 1%
Accuracy	±0.21°C from 0° to 50°C (±0.38°F from 32° to 122°F); see Plot A	±2.5% from 10% to 90% RH (typical), to a maximum of ±3.5% including hysteresis. See Plot B for full range
Resolution	0.02°C at 25°C (0.04°F at 77°F); see Plot A	0.1% RH at 25°C (77°F)
Bits Per Sample	12	10
Drift	<0.1°C (0.18°F) per year	<1% per year typical
Response Time	5 minutes in air moving 1 m/sec	5 minutes in air moving 1 m/sec with protective cap
Operating Temperature Range	-40°C to 75°C (-40°F to 167°F)	
Environmental Rating	Weatherproof: 0 to 100% RH intermittent condensing environments. For best results, the temp/RH smart sensor should be mounted inside a protective enclosure, such as a solar radiation shield.	
Housing	PVC cable jacket with ASA styrene polymer RH sensor cap; modified hydrophobic polyethersulfone membrane	
Sensor Dimensions	10 x 35 mm (0.39 x 1.39 in)	
Weight	S-THB-M002: 110 g (3.88 oz); S-THB-M008: 180 g (6.35 oz)	
Number of Data Channels*	2	
Measurement Averaging Option	No	
Cable Lengths Available	2.5 m (8.2 ft); 8 m (26.2 ft)	
Length of Smart Sensor Network Cable*	0.5 m (1.6 ft); 6 m (19.6 ft)	

CE The CE Marking identifies this product as complying with all relevant directives in the European Union (EU).

* A single HOBO station can accommodate 15 data channels and up to 100 m (328 ft) of smart sensor cable (the digital communications portion of the sensor cables).

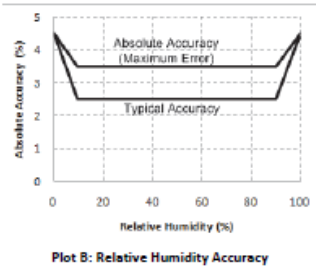
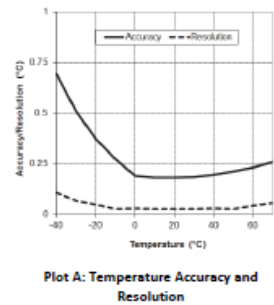
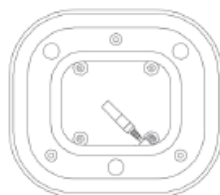


Figure 152: Temperature and Relative Humidity Smart Sensor (S-THB-M00x) Manual
Page 1 of 2 [27]

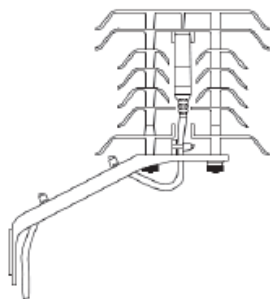
Mounting

Typical Mounting

Solar Radiation Shield: Use the washer and screw (included with the M-RSA radiation shield) or cable clamps (included with the RS3 radiation shield) to secure the smart sensor in the radiation shield as shown at right and below.



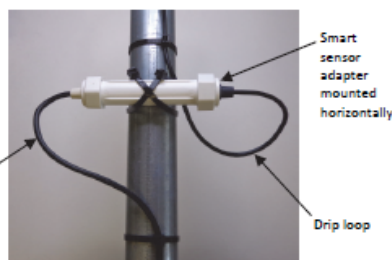
Temp/RH Sensor mounted in the Solar Radiation Shield M-RSA



Temp/RH Sensor mounted in Solar Radiation Shield RS3 (cross-section)

Mounting Considerations

- A solar radiation shield is strongly recommended when measuring air temperature in direct sunlight. Solar radiation can be a significant source of error in the temperature and RH readings.
- When mounting the probe, care should be taken to thermally isolate the sensor from the mounting surface to ensure accurate air temperature and humidity readings. The probe's temperature sensor is at the end of the cable, just below the cup.
- It is recommended that the probe be protected from direct exposure to the weather. This will prolong the sensor accuracy.
- If you are running sensor cables along the ground, it is recommended that you use conduit to protect against animals, lawn mowers, exposure to chemicals, and so on.
- To provide long-term protection from moisture entry, the smart sensor adapter must be mounted horizontally and with the cable wires routed with drip loops so that water drains away from the cable entry point as shown in the next column. When mounted properly, the housing is weatherproof (but not waterproof).
- Refer to the station manual and Tripod Setup Guide for more information regarding setting up stations.



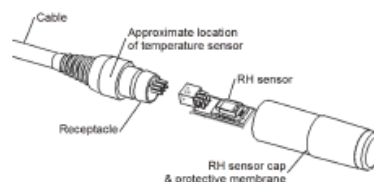
Connecting the Sensor to a Station or Logger

To connect the sensor to a station or logger, stop the station or logger from logging and insert the smart sensor's modular jack into an available smart sensor port. See the station manual for details on operating stations or loggers with smart sensors.

Replacing the RH Sensor

The RH sensor is protected by an ASA styrene polymer cap and a modified hydrophobic polyethersulfone fluid barrier membrane that allows vapor to penetrate while protecting the sensor from condensation. RH sensor performance may degrade over time. To replace the RH sensor, take the following steps:

- Remove the tape fastening the sensor cap to the receptacle. Discard the tape.
- Grasp the cap and membrane and pull firmly to remove them. Discard them.
- Note the orientation of the small circuit board containing the RH sensor. Pull it out and discard it in compliance with local disposal guidelines for circuit boards.



- Push gently but firmly to install the new sensor (HUM-RHPCB-2) in the same orientation.
- Put the new sensor cap and membrane on. Do not force the cap. If it does not go on easily, the sensor may be installed backwards. Reverse the sensor and try again.

Maintenance

The temperature/RH smart sensor is sensitive to dust, salts and other airborne contamination. Periodically inspect the RH sensor. If contamination is present on the protective cap, gently rinse it with cool fresh water. If the sensor itself is contaminated, you can rinse it with distilled water. Do not use hot water, organic solvents, or detergents. Dry before use.

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HOBO Data Loggers

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www.onsetcomp.com • loggerhelp@onsetcomp.com

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11427-K MAN-S-THB

Figure 153: Temperature and Relative Humidity Smart Sensor (S-THB-M00x) Manual
Page 2 of 2 [27]

12-Bit Temperature Smart Sensor (S-TMB-M0xx) Manual



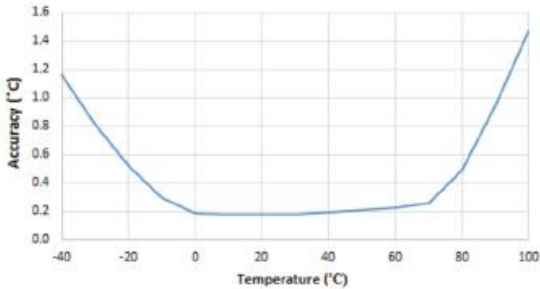
The 12-bit temperature smart sensor is designed to work with HOBO® stations. The smart sensor has a plug-in modular connector that allows it to be added easily to a HOBO station. All sensor parameters are stored inside the smart sensor, which automatically communicates configuration information to the station without any programming or extensive user setup.

Specifications

Measurement Range	-40° to 100°C (-40° to 212°F) – sensor tip
Accuracy	< ±0.2°C from 0° to 50°C (< ±0.36°F from 32° to 122°F), see Plot A
Resolution	<0.03°C from 0° to 50°C (<0.054°F from 32° to 122°F)
Drift	<0.1°C (0.18°F) per year
Response Time	<2 minutes typical, in 2 m/sec (4.5 mph) moving air flow <1 minute typical in stirred water bath
Operating Temperature Range (In-cable Electronics)	-40° to 75°C (-40° to 167°F)
Environmental Rating	Sensor tip and cable jacket: Immersion in water up to 50°C (122°F) for 1 year
Housings	Stainless steel waterproof sensor tip; weatherproof PVC housing for smart sensor adapter
Dimensions	Temperature probe: 5.1 x 33 mm (0.2 x 1.3 inches)
Weight	2 meter: 0.09 g (3.3 oz) 6 meter: 0.14 g (5.2 oz) 17 meter: 0.30 g (11.2 oz)
Bits per Sample	12
Number of Data Channels*	1
Measurement Averaging Option	Yes
Cable Lengths Available	2 m (6.6 ft) S-TMB-M002 6 m (19.7 ft) S-TMB-M006 17 m (55.8 ft) S-TMB-M017
Length of Smart Sensor Network Cable*	0.5 m (1.6 ft) for all models

CE The CE Marking identifies this product as complying with all relevant directives in the European Union (EU).

* A single HOBO station can accommodate 15 data channels and up to 100 m (328 ft) of smart sensor cable (the digital communications portion of the sensor cables).

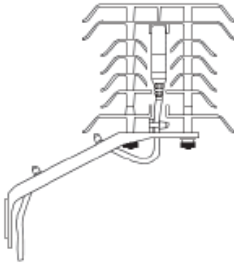


Plot A: 12-Bit Temperature Smart Sensor Accuracy

Figure 154: 12-Bit Temperature Smart Sensor (S-TMB-M0xx) Manual Page 1 of 2 [27]

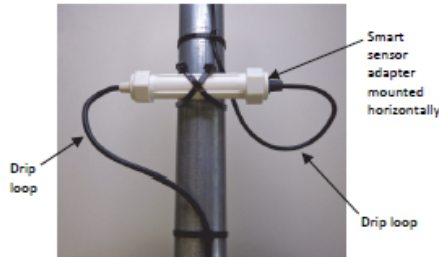
Mounting

Use the cable clamps included with the solar radiation shield (RS3) to secure the smart sensor in the radiation shield as shown at right (see the Solar Radiation Shield manual for additional assembly details).



Mounting Considerations

- Mount the sensor so that at least 10 cm (4 inches) of the sensor cable is placed in the medium that is being measured. The temperature sensor is approximately 0.32 cm (1/8 inch) from the end of the stainless steel tip.
- To provide long-term protection from moisture entry, the smart sensor adapter must be mounted horizontally and with the cable wires routed with drip loops so that water drains away from the cable entry point as shown in the example below. When mounted properly, the housing is weatherproof (but not waterproof).



- If the sensor cable is left on the ground, it is recommended that you use conduit to protect against animals, lawn mowers, exposure to chemicals, etc.
- If you are mounting the sensor in water, place the sensor cable on the side of the mounting post facing downstream. This helps protect the sensor cable from getting damaged by floating debris.
- The solar radiation shield is strongly recommended when measuring outdoor air temperatures. Solar radiation can significantly affect the air temperature readings.
- To minimize measurement errors due to ambient RF, use the shortest possible probe cable length and keep the probe cable as far as possible from other cables.
- Refer to the station manual and Tripod Setup Guide for more information regarding setting up stations.

Connecting the Sensor to a Station

To connect the sensor to a station, stop the station from logging and insert the smart sensor's modular jack into an available smart sensor port on the station. See the station manual for details on operating stations with smart sensors.

Operating Environment

The 12-bit temperature smart sensor can be used in air, soil, or water. The sensor is designed to last at least one year in water as warm as 50°C (122°F). If the smart sensor is continually exposed to water for more than a year, it will eventually drift. Exposure to water above 50°C (122°F) is not recommended and may significantly reduce the life of the sensor.

Response Time

The 12-bit temperature smart sensor has 90% response times of <2 minutes in 2 m/sec (4.5 mph) moving air flow (<1 minute typical in stirred water bath). Faster sensor response times are not always better because they are more likely to be affected by transient conditions. Ideally the response time of a sensor should be the same order of magnitude as the logging interval. For typical logging intervals of 10 to 30 minutes, this smart sensor's response time of <2 minutes is an acceptable match, however, measurement averaging may be useful for longer logging intervals (see the *Operation* section).

Operation

The 12-bit temperature smart sensor supports measurement averaging. When measurement averaging is enabled, data is sampled more frequently than it is logged. The multiple samples are then averaged together and the average value is stored for the interval. For example, if the logging interval is set at 10 minutes and the sampling interval is set at 1 minute, each recorded data point will be the average of 10 measurements. Measurement averaging is useful for reducing noise in the data and preventing aliasing, which can occur when the temperature varies more rapidly than it is being measured. It is recommended that you use measurement averaging whenever the 12-bit temperature smart sensor is placed in an area where the temperatures can change quickly with respect to the logging interval, for example, placed in front of a cycling air vent while using a relatively long logging interval. Note that fast sampling intervals (less than 1 minute) may significantly reduce battery life.

Maintenance

The 12-bit temperature smart sensor does not require any maintenance other than an occasional cleaning. If necessary, rinse the sensor and cable with mild soap and fresh water.

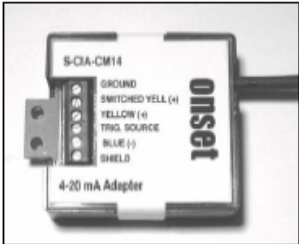
Verifying Accuracy

It is recommended that you check the accuracy of the 12-bit temperature smart sensor annually. The 12-bit temperature smart sensor cannot be calibrated. Onset uses precision components to obtain accurate measurements. If the smart sensor is not providing accurate data, then it may be damaged or worn out if it has been in use for several years. If you are unsure of the smart sensor's accuracy, you can send it back to Onset for re-certification. Contact Onset or your place of purchase for a Return Merchandise Authorization (RMA) number and associated costs prior to sending it.

Figure 155: 12-Bit Temperature Smart Sensor (S-TMB-M0xx) Manual Page 2 of 2 [27]

12-Bit 4-20 mA Input Adapter (Part # S-CIA-CM14)

The 12-Bit 4-20 mA Input Adapter is used for sensors with 4-20 mA current loop outputs and is designed to work with the HOBO® Weather Station and Micro Station data loggers. The input adapter features both a battery-saving switched input and a non-switched input. It also provides a trigger source voltage for controlling power to external sensors. The input adapter has a plug-in modular connector that allows it to be added easily to the HOBO Weather Station or HOBO Micro Station.



Part # S-CIA-CM14

Specification	12-Bit 4-20 mA Input Adapter
Measurement Range*	4-20 mA
Accuracy	± 0.1 mA (± 0.5% full scale) over full temperature range of -40°C to 75°C (-40°F to 167°F)
Resolution	± 4.93 µA
Input Impedance	124Ω
Switched Input	Maximum switch voltage above ground (Pin 2 to Pin 1): 20 V Maximum switch current: 50 mA On time: 316.6 ms ± 3%
Sensor Trigger: Source	Voltage: 2.5 V ± 2.4%; maximum source current: 1 mA On time: 316.6 ms ± 3%
Operating Temperature Range	-40° to 75°C (-40° to 167°F)
Housing	Plastic case; must be placed inside logger enclosure to protect from direct exposure to the weather
User Connection	Six-position screw terminal strip (16 – 30AWG); shielded cable recommended with outside diameter of 3.2 mm to 3.8 mm (0.125 in. to 0.150 in.)
Dimensions	4.5 x 4.8 x 1.6 cm (1.8 x 1.9 x 0.6 in.)
Weight	25 g (0.88 oz)
Number of Data Channels†	1
Measurement Averaging Option	Yes
Digital Filtering	Automatic digital filtering with 32 readings/sample in 16.6 ms
Bits per Sample	12
Length of Network Cable†	14 cm (5.5 in.)
Part Number	S-CIA-CM14

* The input adapter can provide readings as low as 0 mA. This can be helpful when diagnosing sensor issues such as open inputs.

† The HOBO Weather Station and HOBO Micro Station have 10 and 4 data ports, respectively. A single HOBO Weather Station or HOBO Micro Station can theoretically accommodate up to 15 data channels and up to 100 m (328 ft) of network cable (the digital communications portion of the input adapter and smart sensor cables), although available space in the enclosure may limit the number of sensors you can attach.

Figure 156: 12-Bit 4-20 mA Input Adapter (S-CIA-CM14) Manual Page 1 of 6 [27]

12-Bit 4-20 mA Input Adapter

Inside this package

- 12-Bit 4-20 mA Input Adapter
- Hook-and-loop tape
- Three cable ties

Mounting

For the HOBO Weather Station, use the self-adhesive hook-and-loop tape included in the package to mount the input adapter on top of the battery cover inside the logger enclosure. To mount more than one adapter, use the back of the logger enclosure door.

For the HOBO Micro Station, you can place the input adapter inside the logger enclosure and allow it to float freely. It is not necessary to use the hook-and-loop tape.

You can connect up to 10 adapters inside the HOBO Weather Station enclosure, or up to two adapters inside the HOBO Micro Station, based on available space.

Mounting Considerations

- If sensor cables are left on the ground, use a conduit to protect against animals, lawn mowers, exposure to chemicals, etc.
- Refer to the *HOBO Weather Station User's Guide* or the *HOBO Micro Station User's Guide* for information about setting up complete stations.

Attaching Sensor Cables

For the HOBO Weather Station, bring the cable through the opening at the bottom of the logger enclosure. Leave some slack in the cable inside the logger housing so that you can open and close the logger's door and change the batteries without straining the cable connection. Be sure to provide "drip loops" underneath the logger to prevent water from trickling up the cable and into the logger. Pack the opening with duct seal.

For the HOBO Micro Station, bring the cable through the logger's sensor port. (See the *HOBO Micro Station User's Guide* for details on removing the dome nut and stuffing gland from the sensor port.) Ensure that the cables to the sensor are the appropriate size for the stuffing gland (0.125"-0.15"). Be sure to provide "drip loops" underneath the logger to prevent water from trickling up the cable and into the logger.

Use the included cable tie to provide strain relief to the cable (or individual wires), as shown below.



Figure 1: Cable strain relief

12-Bit 4-20 mA Input Adapter

Sensor Input Connections

The 12-Bit 4-20 mA Input Adapter utilizes a 6-position screw-terminal block for sensor connections with wire sizes ranging from 16 to 30AWG. Pin numbers, names and descriptions are as follows.

Pin #	Pin Name	Description
1	GROUND	Ground. Used as a common connection.
2	SWITCHED YELL (+)	Yellow switched. Makes connection to Pin 3 (+ Yellow) once per sample. This helps to conserve external sensor battery life. Maximum 20 V, 50 mA. See "Operation" below for timing diagrams.
3	YELLOW (+)	Positive current input for sampling.
4	TRIG. SOURCE	Triggered source. Provides voltage from the logger's battery to power, or trigger, the external circuitry. Maximum 2.5 V, 1 mA. See "Operation" below for timing diagrams.
5	BLUE (-)	Negative current input for sampling.
6	SHIELD	Connects cable shield for noise suppression and circuit protection.

Typical Setup

A typical remote data logging setup consists of a 12-Bit 4-20 mA Input Adapter, a two-wire 4-20 mA transducer (i.e. flow, pressure, pH, etc.), and an external battery to provide transducer power.

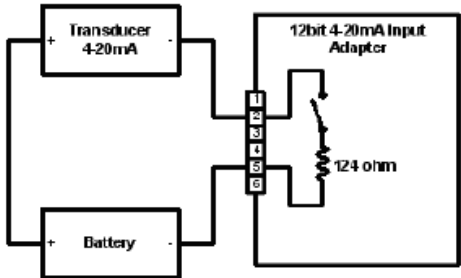


Figure 2: Switched connection

If battery conservation is not an issue, or if longer transducer warmup time is required, the following non-switched connection can be made.

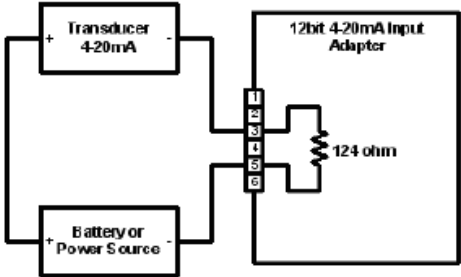


Figure 3: Non-switched connection

12-Bit 4-20 mA Input Adapter

Connecting the Adapters to the Logger

To use the 12-Bit 4-20 mA Input Adapter, stop the logger and insert the adapter's modular jack into an available sensor connection port on the logger. If no port is available, use a 1-to-2 sensor connection adapter (Onset part # S-ADAPT), which allows you to plug two sensors into one port (HOBO Weather Station only).

The logger automatically detects the new input adapter the next time you launch it. Launch the logger and verify that the input adapter is functioning correctly. Measurements are recorded in milliamps (mA). See the *HOBO Weather Station User's Guide* or the *HOBO Micro Station User's Guide* for details.

Operation

The 12-Bit 4-20 mA Input Adapter uses digital filtering and optional measurement averaging to reduce the effect of noise and improve accuracy.

Regardless of whether measurement averaging is used or not, each sample is comprised of a 300 ms ($\pm 3\%$) warmup period and a 16.6 ms ($\pm 3\%$) sample period. During the sample period, digital filtering is accomplished by taking 32 readings. These readings are then averaged to produce a single measurement, as shown in the following diagram:

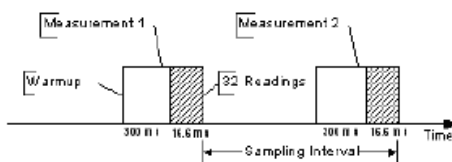


Figure 4: Measurement averaging (not to scale)

Optional measurement averaging can be selected at launch. Use measurement averaging if measurements may fluctuate significantly within the logging interval. Measurement averaging helps to prevent the sampling error known as aliasing.

To use measurement averaging, set the Sampling Interval to a rate that is faster than the logging interval. When measurement averaging is selected in this way, the adapter takes several measurements during the logging interval and averages them to produce a single logged data point. For example, if the logging interval is 10 minutes and the sampling interval is 1 minute, each recorded data point is the average of 10 measurements.

Note that fast sampling intervals (less than one minute) significantly reduce battery life.

For more information about sampling intervals, refer to the *HOBO Weather Station User's Guide* or the *HOBO Micro Station User's Guide*.

12-Bit 4-20 mA Input Adapter

Using the Switched Input

The 12-Bit 4-20 mA Input Adapter can be used with continuously powered 4-20 mA transducers as well as remote applications with external battery-powered 4-20 mA transducers. (See Figures 2 and 3.)

To take advantage of the switched input, the 4-20 mA transducer must meet the following criteria:

- The sensor must be able to be powered from the 4-20 mA loop.
- The sensor must have a warmup time of less than 300 ms.

Using the switched input can significantly reduce external battery consumption because the transducer is powered only during warmup and sampling, as shown in the following diagram, instead of being powered continuously.

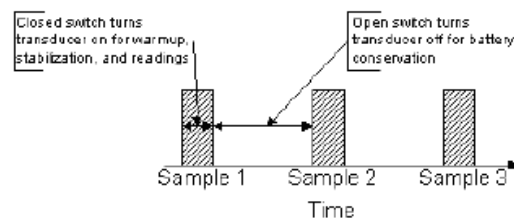


Figure 5: Logging with switched input

Note

- Using an external battery to drive the 4-20 mA transducer does not increase the battery life of the logger (HOBO Weather Station or HOBO Micro Station).

Compared with continuously powering the 4-20 mA transducer, the average current drain is significantly reduced. For an example of the power savings with and without using the switched input:

- If the logger's sampling interval is 60 seconds and the worst case current drain for the transducer is 20 mA, then the average current drain will be:

$$\frac{\text{transducer current} \times \text{sample duration}}{\text{sample duration} + \text{sampling interval}} = \frac{20 \text{ mA} \times 0.327 \text{ s}}{0.327 \text{ s} + 60 \text{ s}} = 0.109 \text{ mA}$$

- If we assume that the transducer battery used has a useful capacity of 2000 mAh, the battery life is:

$$\frac{\text{battery capacity}}{\text{average current}} = \frac{2000 \text{ mAh}}{0.109 \text{ mA}} \div 24 \text{ hr/day} = 764 \text{ days}$$

- Without switched input, the battery life would be:

$$\frac{2000 \text{ mAh}}{20 \text{ mA}} \div 24 \text{ hr/day} = 4.1 \text{ days}$$

Therefore, using the switched input allows the device to run approximately 186 times longer!

12-Bit 4-20 mA Input Adapter**Maintenance**

With normal usage, if the adapter is installed correctly, the adapter's circuitry is protected against excessive moisture and does not require any maintenance or cleaning. However, in an unusually wet environment, excessive moisture can collect in the logger enclosure and adversely affect measurement accuracy and communications in the adapter module.

The circuit board is conformal coated to provide limited protection against moisture, but if you observe heavy condensation, consider the following options:

- Verify that the logger is installed properly and sealed according to the instructions given in the *HOBO Weather Station User's Guide* or the *HOBO Micro Station User's Guide*.
- Consider moving the logger to a location that is better protected from moisture, is better ventilated, or receives some sunlight to help keep the logger dry.
- Apply WD-40, LPS 1, or 711 to the six-position terminal block and the modular connectors to displace moisture and help prevent corrosion. (Other spray lubricants may be appropriate; check product labeling to ensure that it is safe to use on plastics and electronics.)

Verifying Accuracy

You should check the accuracy of the 12-Bit 4-20 mA Input Adapter annually. Verify the accuracy of the input adapter against a known standard, such as a calibrated current source. If it is not providing accurate data, it may have been damaged. If you are unsure of the input adapter accuracy, you can send it back to Onset for re-certification. Contact Onset or your place of purchase for a Return Merchandise Authorization (RMA) number and associated costs prior to sending it.

Warranty

This product is warranted to be free from defects in material and workmanship for a period of one year from the date of original purchase. During the warranty period, Onset will, at its option, either repair or replace products that prove to be defective. This warranty is void if the Onset products have been damaged by customer error or negligence, or if there has been an unauthorized modification.

Tune-up Service

Onset will examine and re-test this input adapter. A tune up fee may be charged.

Figure 161: 12-Bit 4-20 mA Input Adapter (S-CIA-CM14) Manual Page 6 of 6 [27]



F900 Series

Air Velocity and Air Temperature Sensors

Features

- Measures air & inert gas velocity and temperature
- Standard flow ranges between 0.15-10 m/s (approximately 30-2000 fpm)
- Temperature measurements from 0-70°C
- Digital UART Interface
- Linear 0-4 VDC airflow output from 0 to full-scale
- Wide voltage supply: 7-13VDC
- Temperature-compensated from 15-35°C
- Ideal for ducted or open airflow applications
- Available in multiple sensor heads
- Wide acceptance angle ($\pm 30^\circ$)



About the F900

The F900 Airflow Sensor is designed to measure the velocity and temperature of airflows in applications such as HVAC, industrial processes, automotive, air filtration systems, electronics enclosures, and critical containment areas such as biological safety cabinets, fume hoods, and clean rooms.

With standard airflow sensing ranges from 0.15-2 m/s (30-400 fpm) to 0.15-10 m/s (30-2000 fpm), depending on the setting, the Series F900 offers unparalleled price to performance, compact size, reliability and resistance to mechanical shock and vibration.

The F900 series has a linear 0-4V output or a digital TTL output depending on the model. The F900 is easy to install and operate. An adjustable mounting bracket is included with the sensor. In addition, the F900 can be ordered with any of the AccuSense remote sensing head options.

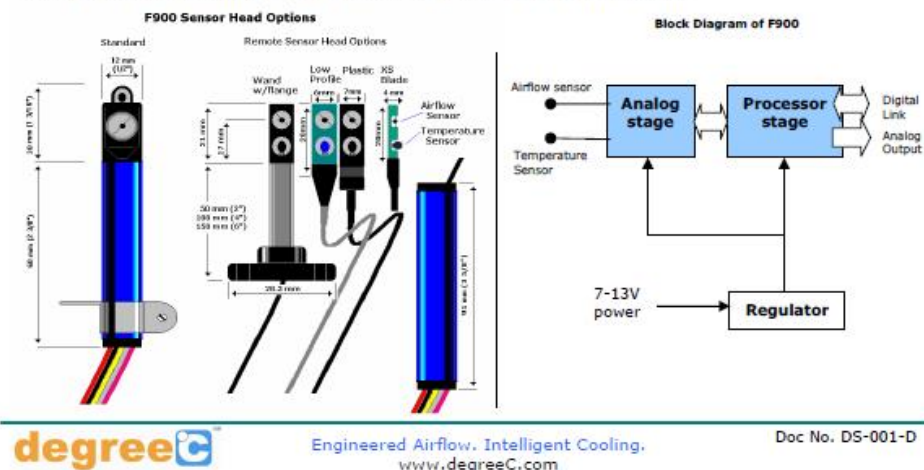


Figure 162: Air Velocity Sensor (T-DCI-F900-L-P) Manual Page 1 of 2 [27]



F900 Series

Airflow Measurement

Standard medium is air at standard pressure (101.3 kPa, 29.95" Hg). For altitude compensation and use with other gases, please contact DegreeC.
 0.15 - 2 m/s (30 - 394 fpm)
 0.15 - 5 m/s (30 - 985 fpm)
 0.15 - 10 m/s (30 - 1969 fpm)

Available Airflow Accuracies

15 - 35°C Greater of $\pm 10\%$ of reading or ± 0.05 m/s (10 fpm) or $\pm 1\%$ of full-scale

15 - 35°C Greater of $\pm 5\%$ of reading or ± 0.05 m/s (10 fpm) or $\pm 1\%$ of full-scale

Output resolution: 4,000 steps.

Repeatability: $\pm 1\%$ under same conditions

Temperature Measurement

Range 0 - 70°C (50 - 140°F)	Available on TTL output only
Accuracy $\pm 1^\circ\text{C}$ above 1 m/s (196 fpm) $\pm 1.5^\circ\text{C}$ below 1 m/s (196 fpm)	Resolution is $\pm 0.1^\circ\text{C}$

Electrical Specifications

Supply Voltage 7-13 VDC	Warm-up Time < 5 seconds
Supply Current 40-75 mA	Operating Temperature 0 - 70°C (32-158°F)
Response Time 1.5 seconds	Storage Temperature -10 to 100°C
Output is linear 0-4 VDC full scale for calibrated range, up to 4.9V beyond calibrated range (airflow only) or TTL level RS-232 (both airflow & temperature).	

Mechanical Specifications

Dimensions	100 mm long X 12 mm diameter for standard unit, 91 mm X 12 mm for long tube with remote sensor heads
Vibration	Up to 25 G's
Acceptance Angles	Standard, rod w/flange, plastic heads are $\pm 30^\circ$, low-profile is $\pm 45^\circ$, XS blade is $\pm 60^\circ$ from perpendicular

Connection Specifications

Pin 1 Black	Supply Return
Pin 2 Red	Supply 7-13 VDC
Pin 3 White	Analog Airflow Output (0-4Vout) for calibrated range, up to 4.9V beyond calibrated range.
Pin 4 Orange	Digital serial output - 19200 BPS, RS232 protocol, TTL level, 8 bit, 1 stop bit - RXD
Pin 5 Yellow	Digital serial input - 19200 BPS, RS232 protocol, TTL levels, 8 bit, 1 stop bit - TXD
Connector	Molex#22-01-2057 or equivalent

Part Number Format

F900 - V - A - B - S - L

V = Velocity Range

N = 0.15 - 2 m/s
 O = 0.15 - 5 m/s
 P = 0.15 - 10 m/s

A = Accuracy Specification

5 = Greater of 5% of reading or ± 0.05 m/s or 1% full-scale
 10 = Greater of 10% of reading or ± 0.05 m/s or 1% full-scale

B = Body Type

0 = Standard (Default) -short tube
 1 = Long tube
 (for remote sensor heads)

S = Sensor Head Type (for B = 1 ONLY)

0 = Plastic
 1 = Low Profile
 2 = 50 mm (2") SS wand /w flange
 4 = 100 mm (4") SS wand /w flange
 6 = 150mm (6") SS wand /w flange
 9 = XS Blade

L = Sensor Cable Length (for B = 1 ONLY)

2 = 2 m

User Manual available at www.degreeC.com



Engineered Airflow. Intelligent Cooling.
www.degreeC.com

Doc No. DS-001-D

18 Meadowbrook Drive Milford, NH 03055 Tel: 603-672-8900 or 1-877-DEGREEC Fax: 603-672-9565

Figure 163: Air Velocity Sensor (T-DCI-F900-L-P) Manual Page 2 of 2 [27]

CONTROL/DISPLAY

Dual DIN Rail Temperature Transmitter

TXDIN70

1 YEAR WARRANTY

CE

✓ Provides Two-Channel Transmitters or Signal Isolators (4 to 20 or 0 to 20 mA)

✓ Programmable Input Types and Ranges with the Optional External Display

✓ DIN Rail Mounted

✓ Use Ungrounded Thermocouple Only

✓ Universal Power Supply

It provides 2 channels of configurable inputs, and supports multiple voltage, RTD, thermocouple inputs with auto reference junction compensation. Each channel has its own digital filtering and can adjust its filtering degree.

• Generates two isolated current outputs, 4 to 20 or 0 to 20 mA

• Range of retransmission output can be freely defined

• The model is DIN rail mounted. Its width is only 22.5 mm

• Can be easily configured by connecting to our E8 handset display

• Universal power supply of 100 to 240 Vac or 24 Vdc

Specifications

Input Type

Thermocouple: K, S, R, E, J, T, B, N, WRe5-WRe26

RTD: Pt100, Cu50

Linear Voltage: 0 to 20 mV, 0 to 60 mV, 0 to 100 mV, 0 to 1V, 0.2 to 1V

Instrument Input Range:

Style K: -50 to 1300°C

Style S: -50 to 1700°C

Style R: -50 to 1700°C

Style T: -200 to 350°C

Style E: 0 to 1000°C

Style J: 0 to 1200°C

Style B*: 0 to 1800°C

Style N: -50 to 1300°C

Style WRe5%WRe26: 0 to 2300°C

Style Pt100: -200 to 900°C

* Note: B thermocouple obtains the measurement accuracy only at the range of 400 to 1800°C. It's measurement from 60 to 400°C is less accurate.

Linear Input: -9990 to 30,000 units defined by user

Retransmission Accuracy: 0.3% full scale ±1 digit (including input and output error)

TXDIN70, DIN rail temperature transmitter.

TXDIN70-DISPLAY, external plug-in display.

Both shown smaller than actual size.

Output Specification: Can be freely defined in the range of 0 to 22 mA with maximum output voltage $\approx 11V$

Temperature Drift: $\pm 0.015\%FS/^{\circ}C$ (including the temperature drift of input and output)

Electromagnetic Compatibility (EMC): ± 4 KV/5 KHz according to IEC61000-4-4 (EFT); 4 KV according to IEC61000-4-5

Isolation Withstanding Voltage: Voltage between power, signal input and output terminals ≈ 2300 Vdc

Power Supply: 100 to 240 Vac, -15%, +10%/ 50 to 60 Hz; or 24 Vdc

Power Consumption: $\approx 3W$

Operating Ambient Temperature: -10 to 60°C; humidity $\approx 90\%$ RH

Dimensions: 100 H x 22.5 W x 100 mm D (3.9 x 0.89 x 3.9")

Weight: 85 g (0.18 lb)

To Order

Model No.	Description
TXDIN70	DIN rail temperature transmitter/isolator
TXDIN70-24V	DIN rail temperature transmitter/isolator 24 Vdc
TXDIN70-DISPLAY	External plug-in display

Comes complete with operator's manual.

Ordering Example: TXDIN70, DIN rail temperature transmitter and TXDIN70-DISPLAY, plug-in display.

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Figure 164: Temperature Transmitter (TXDIN70) Manual Page 1 of 1 [28]