Chapter 6: 
Instrumentation for Research and Management in Animal Agriculture

Roger A. Eigenberg, Ray A. Bucklin, Tami M. Brown-Brandl

Introduction

All living organisms respond to their environment through sensible and latent heat exchange processes. Many problems in animal agriculture involve interactions with environmental factors—temperature, humidity, solar radiation, and wind—which govern these processes. The interplay among temperature, humidity, and solar radiation can be critical, as there is a defined range of thermal conditions within which animals can maintain homeothermy through behavioral and physiological means, while continuing to consume feed at levels needed to maintain production and health (Hahn, 1999). Management decisions for livestock or environmental control systems require accurate environmental measurements. Livestock research also requires accurate monitoring and control of environment to develop needed relationships between such measures for developing models of animal performance.

Instrumentation plays a vital role in the monitoring of physiological responses of animals to their environment. Some of the important responses measured are feed and water intake, heat production, hormone levels, heart rate, respiration rate, body weight, body temperature, and behavioral changes. Some responses, such as respiration rate, can be measured by traditional means, for example using a stop watch while counting flank movements. However, long-term studies requiring frequent measurements can become tedious and labor intensive. Instrumentation to monitor physiological responses is desirable in order to: (1) increase the frequency of measurements to evaluate the dynamics of responses, (2) provide consistent and unbiased data, (3) avoid possible influence of an observer on the animal, and (4) reduce labor requirements for data collection.
Modern instrumentation offers many options for researchers to collect and interpret data on an animal’s environment and its response to that environment. The challenge is to select the appropriate instrumentation for the application at hand. The discussions that follow provide guidance for that task.

### Physiological Measurements

#### Body Temperature

Body temperature is an important parameter when studying livestock stress. For most purposes, measurement of the deep body or core temperature is desired. Up until the 1980s, most measurements of the deep body temperatures of livestock were made using mercury rectal thermometers. After 1980, reliable and affordable electronic dataloggers became available and were used with thermocouples, infrared sensors, and thermistor temperature sensors to replace short-term measurements using mercury thermometers. Continuous temperature measurements are now made using several techniques.

**Rectal Temperature**

Rectal temperatures are measured with a temperature sensor mounted on a rectal probe inserted into the rectum. Rectal probes are easy to insert and are non-invasive. However, rectal probes can only be inserted for a short period of time (2-3 days maximum) without irritating tissue, and measurements can be affected by cool blood returning from the lower extremities, insulation by feces, and heat produced by bowel organisms. Rectal temperatures are usually a few tenths of a degree higher than arterial blood temperatures. Dynamic rectal temperatures have been collected for nearly all livestock and poultry species (Hahn et al., 1990; Brown-Brandl et al., 1997; Brown-Brandl et al., 2001; Brown-Brandl et al., 2003a; Silanikove, 2000; Lin et al., 2005b; Lin et al., 2005a; Ott, 2005; Marai et al., 2007; Piccione et al., 2007).

**Tympanic Temperature**

The temperature of the tympanic membrane within the ear closely approximates hypothalamic temperature and is a reliable method of measuring core temperature although the accuracy of tympanic temperature probes can be limited by wax in the ear canal (Guidry and McDowell, 1965; Wiersma and Stott, 1983; Hahn et al., 1990; Brown-Brandl et al., 1999; Paul et al., 1999; Bergen and Kennedy, 2000; Mader, 2005). These probes may be periodically switched between ears to obtain continuous long-term records.

Skill is required to properly place tympanic probes. They need to be reinstalled every 7 to 10 days to avoid ear infections. However, the process of inserting the probe becomes increasingly stressful for the animal. The probes can be secured by either prosthetic foam, which expands and fills the ear canal, or by a modified ear-tag button, which secures the probe by using nylon tie straps and the ear tag (Brown-Brandl, 1999).

This method has been used successfully in cattle, sheep, and pigs. Pigs need to be placed under anesthetic to allow for proper placement.

**Vaginal Temperature**

Vaginal temperatures can also be used for monitoring body temperature (Bray et al., 1990; Bray et al., 1991; Bray et al., 1993; Bergen and Kennedy, 2000; Brouk et al., 2007).
The temperature sensors can either transmit signals to an external receiver coupled to a datalogger or the sensor can be an integrated sensor/logger combined in a single package (e.g., Onset Computer Corporation). Irritation and infection resulting from the inserted devices can be minimized by placing the sensor unit in a flexible plastic sleeve (Hillman et al., 2005). Vaginal temperatures have been collected for up to three weeks with only minimal irritation using the flexible sleeve and the combined sensor datalogger. The flexible sleeve with datalogger method has been used in both dairy cows and beef heifers. The system is too large for using in smaller species.

**Digestive Tract Temperature**

Temperature sensors combined with dataloggers or radio transmitters can be swallowed by livestock to measure temperatures in the digestive tract (Hicks et al., 2001; Schoenig et al., 2004). Sensors remain within the rumen or reticulum of ruminants or eventually pass through the digestive tract of non-ruminant mammals. When used with poultry, these sensors remain in the gizzard. The overall size of ingestible temperature sensors is usually governed by the size of the required battery. Sensors that pass through the digestive tract can be small, but if the sensor remains in the rumen or gizzard, and measurements are desired over a prolonged period, battery size increases. The presence of toxic materials in batteries and sensor components is a concern for the use of sensors involving animals that will enter the food chain.

Temperatures in the digestive tract vary over time and typically differ from other organs. Food in the stomach affects temperature readings and rumen temperatures are affected by fermentation processes. Temperature sensors can sometimes be regurgitated, particularly by ruminants. Temperature sensors in poultry have a lifetime of not more than a few days because of the grinding action of the gizzard.

**Implanted Sensors**

Temperature sensors coupled with radio transmitters can be implanted in body cavities of animals to give continuous readings over prolonged periods (Lefcourt and Adams, 1996, 1998; Hamrita et al., 1998; Hicks et al., 2001; Brown-Brandl et al., 2003b; Mitchell et al., 2005). Overall size and implant life is largely governed by battery size. Surgery is required to implant the sensors and veterinary assistance is usually required. Batteries and sensor components are also an issue for field trials or commercial use of sensors involving animals that will enter the food chain. Implanted systems are expensive and require a high level of veterinary and technical support to operate. Many available implantable sensors are equipped with transmitters with short ranges, requiring a receiver and datalogger to be strapped to the animal.

A new field of MEMS (micro-electro-mechanical systems) technology offers the potential to greatly improve the usability of implanted sensors. MEMS devices and sensors have sizes ranging from nanometers to millimeters. MEMS sensors can be powered by energy emitted from adjacent antennas and eliminate the need to implant batteries. MEMS devices are much less invasive than presently available sensors and have the potential to provide separate readings for particular organs in an animal. A specific limitation is the need to have an antenna mounted in close proximity to the animal. If continuous monitoring is not required, periodic readings may be obtained by mounting an antenna on a gate or chute.
Respiration

For most mammals (homeotherms), respiratory heat transfer is a significant mechanism of heat loss under a wide range of environmental conditions (Ingram and Mount, 1975). Respiration rate is of particular interest as a physiological response because a large body of research shows a positive correlation between respiration rate and dry-bulb temperature (Kibler and Brody, 1949; Webster, 1974; Ingram and Mount, 1975; Morrison and Lofgreen, 1979; Liao and Veum, 1994; Hahn et al., 1997; Brown-Brandl et al., 1998; Mader et al., 1999; Gaughan et al., 2000; Mitlöchner et al., 2001; Eigenberg et al., 2005) Additionally, an increased respiration rate has been associated with an increase in solar radiation (Spain and Spiers, 1996), increased relative humidity (McLean, 1973), and decreased wind speed (Mader and Davis, 2002).

The respiration rate has been shown to be a good indicator of thermal stress and has the advantage of being readily observable in a production setting. It demonstrates little lag time relative to dry-bulb temperature, so it readily reflects an animal’s thermal status. Furthermore, respiration rate has a demonstrated capacity to be useful in distinguishing among stress-susceptible cattle in feedlots. The relative stress level, as measured by respiration rate, is influenced by genotype (especially differences in genotype associated with hide color differences), health history, and temperament. Monitoring of respiration rate shows promise in precision animal management for identifying animals that may be vulnerable to heat stress. Monitoring allows those animals to be sorted and treated differently than the main herd.

Automated Monitoring of Respiration Rate in Cattle

An example (Eigenberg et al., 2000) of an automated cattle respiration rate monitor is included here to document the methodology. A thin-film transducer (designed for human application) is incorporated into a silicone rubber strain assembly and used to sense changing thoracic or abdominal circumference in cattle. The device is mounted with two bungee cords that span the abdominal circumference (Figure 1), with each

Figure 1. The cattle abdominal expansion sensor is held in place by using two lightweight bungee cords to span the abdominal circumference. The datalogger is secured in a pocket on the harness assembly (Eigenberg et al., 2000).
Figure 2. The swine acoustic sensor microphone is held in place under the pig’s neck with elastic bandaging. The datalogger is secured in a pocket on the upper harness assembly (Eigenberg et al., 2002).

end of the cords attached to a ring on either side of the sensor. The cords form a belt, providing a constant tension and holding the sensor in place. The respiratory-effort transducer used for cattle generates a variable resistance in response to respiration. Amplification and offset compensation produce a signal that is compatible with the voltage range requirements of the datalogger, which is attached to the animal via a harness assembly.

Automated Monitoring of Respiration Rate in Swine

An automated device to measure respiration rate in swine has also been demonstrated (Eigenberg et al., 2002). An expansion sensor similar to that used on cattle proved unsuccessful in measuring respiration rate of swine because swine spend much of their time in the recumbent position and have less definitive respiratory movements than cattle. Tests determined that an audible component of the pig’s respiration has the potential of being detected and recorded. Thus, the sensor is a small microphone that is placed under the throat of the pig and held with standard elastic bandaging (Figure 2). Sensor location is critical for maximum response and reduced noise. The acoustic signal is conditioned to produce a signal compatible with the datalogger attached to the pig via a harness assembly.

Behavioral Measurements

Animal presence, activity, and to some extent behavior has been successfully monitored using various electronic devices. Activity such as standing versus recumbent behavior has been electronically documented using an ultrasonic positioning range-finding device. This device measures the distance between the sensor and an object which has been used to monitor animal presence in a stall (Hillman et al., 2000) and animal activity in a confined space (Brown-Brandl et al., 2000).

Animal behavior is much more complex than simply presence or activity in an area. For a comparatively simple example, measuring the huddling area of piglets requires a digital image of the animals. This can be analyzed for the huddling area occupied by the piglets using machine vision (Zhang and Xin, 2005). Actually being able to electronically recognize a specific animal behavior requires the development and training
of a computer vision system. In order to assess images for behavior the images must be collected with relatively high frequency. Information can be collected using these digitized images by defining key components of the image using numerical equations. The system is then calibrated by assigning behaviors based on visual observation and then determining the values of the parameters from the numerical equations. Then, in subsequent videos the behaviors can be identified based solely on the values of the parameters (Leroy et al., 2006; Xue and Henderson, 2006)

**Meteorological Measurements**

**Air Temperature**

Air temperature is a major factor influencing the metabolism of livestock. It is of particular importance when ambient air temperatures are outside the animal’s thermoneutral zone. Outdoor weather conditions vary from approximately –50°C in the winter in northern areas to 50°C in arid areas near the equator. Temperatures inside livestock housing are normally kept above freezing and should not exceed the upper limit of the thermoneutral zone, but temperatures approaching 40°C may be observed in some poorly managed facilities.

Environmental monitoring requires the measurement of ambient air temperature. Whatever type of sensing element is used, care must be taken that the actual ambient air temperature is measured. Temperature sensing elements are sensitive to the effects of radiation and must be shielded from objects either hotter or colder than the air temperature. The most common object fitting this definition is the sun. However, any object in the field of view of a thermometer at a temperature differing from the air temperature will exchange energy by radiation with the sensor and affect the reading. An unshielded temperature sensor located outside on a summer day will indicate temperatures well above the actual air temperature. This effect can be avoided by placing a reflective ventilated shield between the sun and the sensor. The temperature sensor must also be located in a well-ventilated area to provide a true measure of ambient air temperature. In some cases, this will require the use of a small fan located downstream of the sensor to move air over the sensing element. Care should also be taken to not mount temperature sensing elements directly onto metal surfaces that easily conduct heat to or away from the sensor.

Devices that measure temperature rely on the change in some physical property with temperature (Mitchell, 1983; Doebelin, 1990; ASHRAE 2001). The temperature of a given object is related to its degree of molecular motion; the more disorder that exists in the random motions of an object’s molecules, the higher are the heat content and temperature of that object. An object’s temperature may be registered by any property that depends on that object’s thermal state. Such properties range widely and include volume (at constant pressure), electrical resistance, semiconductor junction potential, resistivity of a pure metal, resistivity of oxides of transition metals, thermal voltage associated with dissimilar metals, and even visible color, since objects become luminous when their temperatures rise sufficiently. The assignment of a particular number value to a given temperature state is arbitrary but for research applications the Celsius or centigrade scale (in which freezing water is 0°C and boiling water is 100°C) is used.
### Table 1. Air temperature measurement methods.

<table>
<thead>
<tr>
<th>Type</th>
<th>Principle</th>
<th>Typical Accuracy</th>
<th>Typical Stability</th>
<th>Electronic Interface</th>
<th>Comments</th>
<th>Approx. Range</th>
<th>Relative Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Expansion: Liquid</strong></td>
<td>measure expansion of a liquid</td>
<td>very accurate and are used as standards</td>
<td>very repeatable</td>
<td>no direct electrical output</td>
<td>slow response, time, fragile, expensive, narrow range</td>
<td>wide</td>
<td>medium</td>
</tr>
<tr>
<td><strong>Expansion: Gas</strong></td>
<td>measure the volume variation of a gas</td>
<td>very accurate and used as standards</td>
<td>very repeatable</td>
<td>no direct electrical output</td>
<td>bulky, expensive</td>
<td>wide</td>
<td>high</td>
</tr>
<tr>
<td><strong>Expansion: Bimetallic strip</strong></td>
<td>spring-like mechanism made of metals with differing thermal expansion coefficients</td>
<td>1.0°C exhibit hysteresis and are not very precise</td>
<td>no direct electrical output</td>
<td>rugged, slow reaction time, inexpensive</td>
<td>wide</td>
<td>low</td>
<td></td>
</tr>
<tr>
<td><strong>Electrical resistance: Thermistor</strong></td>
<td>semiconductor compounds that exhibit large resistance changes as temperature changes</td>
<td>0.1 to 0.5°C, depending on signal conditioning design</td>
<td>repeatable</td>
<td>requires signal conditioning and response is non-linear</td>
<td>moderate response times and depends on self-heating effects</td>
<td>wide</td>
<td>low</td>
</tr>
<tr>
<td><strong>Electrical resistance: Resistance temperature detectors (RTD)</strong></td>
<td>fine coil of platinum or nickel alloy as sensing element</td>
<td>0.1°C</td>
<td>repeatable</td>
<td>very linear, requires signal conditioning to interface to computer</td>
<td>slow response times, more expensive than thermistors</td>
<td>wide</td>
<td>medium</td>
</tr>
<tr>
<td><strong>Thermocouples</strong></td>
<td>dissimilar metals produce voltage dependent on junction temperatures</td>
<td>0.1 to 0.5°C, depending on cold bridge junction, amplification, and # ADC bits</td>
<td>stable</td>
<td>requires signal amplification and conditioning</td>
<td>response dependent on gauge size; rugged, adaptable to many applications</td>
<td>wide</td>
<td>low</td>
</tr>
<tr>
<td><strong>Radiation: Infrared thermocouples</strong></td>
<td>thermocouples in series depends on knowledge of emissivity of target</td>
<td>stable</td>
<td>direct interface/ non-linear</td>
<td>no physical contact, rugged, fast response; averages temperature over field of view (FOV)</td>
<td>wide</td>
<td>high</td>
<td></td>
</tr>
<tr>
<td><strong>Radiation: Infrared thermometer</strong></td>
<td>measures energy emitted from target depends on knowledge of emissivity of target</td>
<td>stable</td>
<td>direct interface</td>
<td>no physical contact with target, fast response, averages temperature over field of view (FOV)</td>
<td>wide</td>
<td>high</td>
<td></td>
</tr>
<tr>
<td><strong>Semiconductor thermometer</strong></td>
<td>semiconductor junction voltage or current directly related to temperature</td>
<td>0.1°C</td>
<td>stable</td>
<td>direct interface, linear output</td>
<td>linear output; generally, slow response</td>
<td>-25 to 200°C</td>
<td>low</td>
</tr>
</tbody>
</table>
When observing animal responses, it is desirable to measure conditions as close to the animal as possible, and thus destruction of sensors by livestock is a common problem. Another problem is that animal environments are often dusty and dust accumulation can affect the accuracy of sensors.

Table 1 lists some pertinent characteristics of various temperature sensors. Temperatures of environments surrounding animals within housing structures or in open lot settings can be measured successfully using thermocouples or thermistors. Thermocouples (T/C) offer advantages of durability, relatively low cost and versatility. Grids of thermocouples can easily be assembled using equal length T/C wire connected in parallel to a single wire. This wire can be run a suitable distance to the datalogger where the average temperature of all T/C connections in the grid can be measured. Thermistors offer a good solution where a small number of measurement points can be connected to a suitable datalogger located near the sample points.

**Air Speed**

Air speed is measured in an open environment to understand macroscale wind patterns around livestock buildings. It is also measured locally in ducts and around air-handling devices to understand air movement in housing facilities. It is measured in the neighborhood of livestock to understand the heat and mass exchanges of the animal. High wind speeds (velocities over 50 m/s, as in storms) are important considerations for structural analysis and design of buildings. However, the air speeds of interest for livestock are below 10 m/s. Wind speeds below 0.2 m/s are typically regarded to be still air.

The terminology associated with measurement of air movement describes air velocity as a vector quantity possessing magnitude and a direction. Air speed is simply the magnitude of air velocity (Mitchell, 1983; Doebelin, 1990; ASHRAE 2001).

Air speed can be measured in a number of ways based on mechanical methods, pressure relationships, thermal principles, and the Doppler effect. Air speed is measured by anemometers. A wide variety of anemometers are available, including numerous versions of the following major types: rotational, pressure, deflection, thermoelectric, and Doppler.

Some anemometers are non-directional and give only the maximum speed, some use wind vanes to orient instruments and measure direction, and others combine multiple sensors to obtain both magnitude and direction to yield velocity. Air speeds usually fluctuate and consideration should be given to the instrument response time if the goal is to measure gusts or other rapid changes in speed. Another consideration is that anemometers are usually delicate instruments and must be protected if located close to animals. Often only hand-held instruments are used in close proximity to animals. Also, the sensing mechanisms of anemometers are easily affected by coatings of dust.

Rotational cup anemometers are a good choice for wind speed measurements at outdoor sites such as near feedlots or other outdoor meteorological sites. Air speed measurements in buildings may require a more sensitive measurement as achieved by a hot wire anemometer. Any instruments used for monitoring environmental conditions near animal locations must be protected from direct access by the animals. Table 2 lists various options for air speed measurement.
<table>
<thead>
<tr>
<th>Type</th>
<th>Principle</th>
<th>Typical Accuracy</th>
<th>Typical Stability</th>
<th>Electronic Interface</th>
<th>Comments</th>
<th>Approx. Range</th>
<th>Relative Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cup anemometer</td>
<td>wind powered turbine in the form of cups mounted on radial spokes</td>
<td>1 m/s</td>
<td>stable</td>
<td>pulse count into logger</td>
<td>omni-directional in plane of rotation of cups</td>
<td>wide</td>
<td>low</td>
</tr>
<tr>
<td>Propeller anemometer</td>
<td>wind powered turbine in the form of a propeller</td>
<td>1 m/s</td>
<td>stable</td>
<td>pulse or voltage out to logger</td>
<td>more responsive to gusts than cup anemometers, must be oriented into the wind</td>
<td>1 to 40 m/s</td>
<td>medium</td>
</tr>
<tr>
<td>Pressure plate anemometer</td>
<td>plate pivots about horizontal axis above center of gravity, angular deflection is measure of air velocity</td>
<td>5 m/s</td>
<td>stable</td>
<td>difficult to interface</td>
<td>must be oriented into the wind, have natural resonant frequency resulting in fluttering</td>
<td>1 to 40 m/s</td>
<td>low</td>
</tr>
<tr>
<td>Pitot tube and orifice plates</td>
<td>measure difference between dynamic and static pressure of air based on pressure difference</td>
<td>1 m/s</td>
<td>stable</td>
<td>requires pressure transducers to provide interface</td>
<td>pitot tube must be aligned with the air stream</td>
<td>1 to 40 m/s</td>
<td>medium</td>
</tr>
<tr>
<td>Thermo-electric: Hot wire anemometer</td>
<td>airflow over heated wire cools the wire by convection and changes the resistance</td>
<td>0.1 m/s</td>
<td>requires frequent calibration</td>
<td>requires interface</td>
<td>measures very low air speeds since can respond to small changes; orientation sensitive</td>
<td>0.1 to 20 m/s</td>
<td>medium</td>
</tr>
<tr>
<td>Doppler: Sonic anemometer</td>
<td>time difference between an ultrasonic wave traversing through moving air and a reference signal</td>
<td>1 m/s</td>
<td>stable</td>
<td>requires interface</td>
<td>no moving parts; can take thousands of readings per second</td>
<td>1 to 100 m/s</td>
<td>high</td>
</tr>
<tr>
<td>Laser anemometer</td>
<td>measure Doppler shift of moving airborne particle (such as dust)</td>
<td>1 m/s</td>
<td>stable</td>
<td>requires interface</td>
<td>can measure air velocity profiles up to 150 m from instrument; complex circuitry</td>
<td>1 to 100 m/s</td>
<td>high</td>
</tr>
</tbody>
</table>

**Humidity**

Clean, dry air is a mixture of atmospheric gases that includes \( \text{N}_2 \) (78.08%), \( \text{O}_2 \) (20.95%), \( \text{Ar} \) (0.93%) and other trace gases in much smaller quantities (Harrison, 1963). Water vapor (\( \text{H}_2\text{O} \)) is the most variable constituent of the atmosphere. Its percentage by volume relative to all other gaseous constituents may range from as little as
0.000002% at high altitudes and cold conditions to nearly 5% in subtropical or equatorial regions. The water vapor content varies with meteorological conditions, but at middle latitudes the average water vapor content usually lies in the range of about 1.0% to 1.5% by volume (Harrison, 1963).

The water vapor content of moist air, or humidity, is determined by a variety of approaches in the following categories: absolute methods, thermometric methods, chemical methods, electric/electronic methods, radiometric methods, and hygroscopic methods (Kostyrko, 1968). The parameters for quantifying the amount of water vapor (Quinn, 1985) in a gas include the humidity ratio, specific humidity, mole ratio, mole fraction, absolute humidity, saturation water vapor pressure, dew-point temperature, frost point temperature, relative humidity, percent saturation, dry-bulb and wet-bulb temperatures, adiabatic saturation temperature, thermodynamic wet-bulb temperature, percent equilibrium relative humidity, and water activity. Of these, only relative humidity (RH) will be considered here.

Relative humidity is the ratio of the mole fraction of water vapor in air to the mole fraction of water vapor in air at saturation, which is also equal to the ratio of the partial pressure of water vapor in a space to the partial pressure of water vapor in the space at saturation (ASHRAE, 2001), or:

\[
RH = \frac{X_W}{X_{WS}} = \frac{P_W}{P_{WS}}
\]

where RH = relative humidity

\[
X_W = \text{mole fraction of water in air}
\]

\[
X_{WS} = \text{mole fraction of water in air at saturation}
\]

\[
P_W = \text{partial pressure of water vapor}
\]

\[
P_{WS} = \text{partial pressure of water vapor at saturation}
\]

Relative humidities close to 100% occur in poorly ventilated livestock housing and relative humidities below 10% are common in arid areas.

Several methods are available to measure humidity and relative humidity. Unfortunately, none of them are totally satisfactory based on rugged design, range, and accuracy. If possible, humidity sensors should be housed within the same aspirated radiation shield as the dry-bulb temperature sensor. If a fan is used to aspirate the sensor, it must be located downstream from the humidity sensor. Humidity sensors must be protected from contaminants such as salt, hydrocarbons, and other particulates. The best protection is the use of a porous membrane filter that allows the passage of ambient air and water vapor while keeping out particulate matter. Any sensor that measures relative humidity by calibrating the change in the physical or electrical properties of a sensing element to changes in the relative humidity must be frequently checked for proper calibration (Mitchell, 1983; Doebelin, 1990; ASHRAE 2001).

The best humidity sensors suitable for field use are rated by their manufacturers as having accuracies of 2%. In practice, very few humidity sensors have accuracies better than 5%. Some humidity sensors are damaged by condensation and many sensors lose calibration when condensation occurs and no longer read correctly. Many of the electronic sensors also lose accuracy in the presence of certain chemical contaminants.

Table 3 lists a variety of humidity sensors and characteristics of each. Practical experience has shown that in precision applications such as calorimetry a chilled...
Table 3. Humidity measurement methods.

<table>
<thead>
<tr>
<th>Type</th>
<th>Principle</th>
<th>Direct Measure</th>
<th>Typical Accuracy</th>
<th>Electronic Interface</th>
<th>Comments</th>
<th>Approx. Range</th>
<th>Relative Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet-bulb psychrometer</td>
<td>aspirated wetted wick attached to temperature sensor</td>
<td>wet-bulb temperature</td>
<td>0.1°C</td>
<td>with suitable</td>
<td>wick must be clean, not good in dusty environments; needs continuous</td>
<td>wet-bulb</td>
<td>low</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>temperature</td>
<td>supply of water, minimum air velocity over wick, and dry-bulb temperature</td>
<td>temperature</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>sensor</td>
<td>upstream.</td>
<td>above freezng</td>
<td></td>
</tr>
<tr>
<td>Chilled mirror hygrometer</td>
<td>mirror chilled thermoelectrically until moisture forms on surface, change in</td>
<td>dew point</td>
<td>0.1°C</td>
<td>sophisticated cooling and sensing required</td>
<td>very accurate, used for standards, not good in dusty environments</td>
<td>dew points</td>
<td>high</td>
</tr>
<tr>
<td></td>
<td>mirror optics triggers mirror (dew-point) temperature measurement</td>
<td></td>
<td></td>
<td>cooling and sensing</td>
<td></td>
<td>above freezng</td>
<td></td>
</tr>
<tr>
<td>Surface acoustic wave sensor</td>
<td>piezoelectric transducer generates acoustic wave that changes propagation characteristics as dew forms</td>
<td>dew point</td>
<td>1%</td>
<td>sophisticated cooling and sensing required</td>
<td>less affected by contamination than chilled mirror with faster response times</td>
<td>dew points</td>
<td>high</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>cooling and sensing</td>
<td></td>
<td>above freezng</td>
<td></td>
</tr>
<tr>
<td>Hair hygrometer</td>
<td>diffusion equilibration between hair’s water content and water vapor content of air causes hair to lengthen and contract</td>
<td>relative humidity</td>
<td>10%</td>
<td>not easily interfaced</td>
<td>require frequent calibration, fragile; not recommended in livestock facilities</td>
<td>10% to 90%</td>
<td>low</td>
</tr>
<tr>
<td>Capacitance hygrometer</td>
<td>change of dielectric constant between capacitor plates in response to humidity changes</td>
<td>relative humidity</td>
<td>10%</td>
<td>signal conditioning required</td>
<td>not recommended in livestock facilities</td>
<td>10% to 90%</td>
<td>medium</td>
</tr>
<tr>
<td>Substrate or polymer-based sensors</td>
<td>electrical impedance of a hygroscopic medium such as a conductive polymer changes with humidity</td>
<td>relative humidity</td>
<td>10%</td>
<td>signal conditioning required</td>
<td>short lifetime in the presence of chemically active vapors found in livestock facilities</td>
<td>10% to 90%</td>
<td>medium</td>
</tr>
<tr>
<td>Lithium chloride-based sensors</td>
<td>electrical current is passed through lithium chloride until equilibrium temperature is reached; equilibrium temperature is dependent on relative humidity</td>
<td>relative humidity</td>
<td>1%</td>
<td>signal conditioning required</td>
<td>needs frequent calibration, recommended for laboratory use only</td>
<td>5% to 95%</td>
<td>high</td>
</tr>
</tbody>
</table>
mirror hygrometer offers the accuracy needed to measure moisture changes for inlet and outlet air. The air to the instrument must be filtered to prevent contamination and a periodic calibration and cleaning schedule must be followed to maintain required performance. Harsh environments, such as livestock buildings, can use the thermal conductivity methods with success. Accuracy is diminished at lower temperatures but the sensors can handle high temperatures, corrosive gases, and dust.

**Solar Radiation**

The sun supplies virtually all the energy received by the earth. The sun has a spectral distribution that is roughly that of a blackbody with a peak at a wavelength of 0.5 μm and a spectral distribution reaching the Earth’s surface ranging from infrared (10 μm) through ultraviolet (0.3 μm). The amount of solar radiation reaching a horizontal unit of the earth’s surface depends on a number of factors that include the transparency of the atmosphere, the intensity of the radiation emanating from the sun, and astronomical considerations that determine the position of the sun (Rosenberg, 1974). The mean annual intensity of solar radiation above the atmosphere is close to 1367 W/m² and the solar intensity at the Earth’s surface can exceed 1000 W/m² on a clear day at noon.

In addition to the radiation emitted by the sun, radiation is also emitted by terrestrial sources, such as plants, the soil surface, and buildings. Radiation is classed as shortwave (0.3 μm to 4.0 μm) and longwave (4.0 μm to 100 μm). Shortwave radiation refers to radiation that originates at the sun, whether it is direct, reflected, or diffuse (scattered by clouds). Longwave radiation generally refers to radiation that originates from terrestrial sources and is generated by the temperature of that source. Global radiation is the sum of direct and diffuse radiation reaching a surface and does not include longwave radiation. Net radiation is the sum of direct and diffuse radiation, plus incoming longwave radiation and minus the sum of reflected shortwave radiation and outgoing longwave radiation. Net radiation is the net energy transmitted to a surface (Garrison and Roeder, 1999).

| Table 3 (continued). Humidity measurement methods. |
|---------------------------------|----------------|----------------|----------------|----------------|----------------|----------------|
| Thermal conductivity sensors    | self-heated bridge circuit using two thermistors and two resistors, one thermistor is glass encapsulated and one is not; bridge circuit imbalance is proportional to absolute humidity | absolute humidity | 5% signal conditioning required | very durable and resistant to chemical vapors | 10% to 95% | medium |
| Infrared absorption hygrometer  | water absorbs electromagnetic radiation in infrared region of the spectrum | relative humidity | 5% signal conditioning required | slow reaction times, must be protected from dust | 10% to 90% | high |
Table 4. Solar thermal radiation measurement methods.

<table>
<thead>
<tr>
<th>Type</th>
<th>Principle</th>
<th>Typical Accuracy</th>
<th>Typical Stability</th>
<th>Electronic Interface</th>
<th>Comments</th>
<th>Approx. Range</th>
<th>Relative Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eppley pyranometer</td>
<td>thermopile with hot and cold areas (black and white); sensor enclosed in glassed dome that permits solar radiation to reach sensor</td>
<td>high</td>
<td>stable</td>
<td>compensation for temperature required</td>
<td>millivolt output nearly linear with solar radiation flux density; glass dome is a lens that corrects for cosine effects</td>
<td>0.2 to 4.5 μm</td>
<td>medium</td>
</tr>
<tr>
<td>Black globe radiation</td>
<td>Vernon globe thermometer consists of 15-cm globe sphere coated with flat black paint with a thermocouple at the center</td>
<td>0.2°C stable</td>
<td>same as for thermocouple</td>
<td>slow response (20 to 30 min); temperature at center of globe is a measure of mean radiant temperature when air velocity is zero</td>
<td>0.3 to 10 μm</td>
<td>low</td>
<td></td>
</tr>
<tr>
<td>Silicon photodiode pyranometer sensors</td>
<td>calibrated photoelectric sensor</td>
<td>5% stable</td>
<td>needs a precision resistor to convert current to voltage output</td>
<td>less expensive than pyranometers; fast response; usually designed only for solar radiation</td>
<td>0.4 to 1.1 μm</td>
<td>medium</td>
<td></td>
</tr>
</tbody>
</table>

Solar radiation instruments for general use include devices that measure direct radiation from the sun, total or global radiation coming from the sky hemisphere, and diffuse radiation (global radiation with the direct radiation removed) (Table 4). Radiant energy is commonly measured by detecting temperature changes of a surface exposed to radiation or by the response of a photoelectric cell. Instruments should be located so that their view is free of obstructions above the horizontal plane of the instrument and care should be taken to ensure that walls or other surfaces do not reflect light onto the instrument. Livestock facilities are dusty and instruments must be checked and cleaned regularly for proper operation. Also, instruments located close to animals can be damaged.

Pyranometers are the most common type of instrument used to measure solar radiation for studies involving livestock. Pyranometers measure total direct and diffuse solar radiation. A pyranometer has a glass dome that allows the solar spectrum to heat white and black areas. The glass dome is also a lens which corrects for cosine effects at various sun angles. A differential thermopile is installed beneath the white/black regions. The difference in temperature measured by the thermopile is linearly correlated with solar radiation flux density.
Devices based on silicon photocells are also used to measure solar radiation. They are less expensive but also less accurate than instruments based on thermopiles. Their spectral response is usually limited to wavelengths from 0.4 μm to 1.1 μm. Photocell sensors have zero sensitivity above about 1.1μm and their spectral response below 1.1μm is not as constant as thermopile-based instruments.

The globe temperature device integrates radiant heat exchange and convective heating or cooling into a single value that can be used to calculate the mean radiant temperature (ISO, 2001). The Vernon Globe Thermometer (Vernon, 1932) is the standard instrument for measuring the globe temperature. The Vernon Globe consists of a 15-cm hollow copper sphere with 0.056 cm thick walls painted flat (matte) black on the outside and containing an unshielded dry-bulb thermometer or its equivalent in the center of the sphere. Globe thermometers include solar and terrestrial radiation, and are quite useful in that regard. The emissive characteristics of skin approach those of a black sphere, so the temperature balance of the sphere is a measure of the net radiative heat transfer of livestock (Bond and Kelly, 1955). Air velocity measurement is required to obtain radiation measures from black globes. Black globes of other diameters also can be used in livestock studies (Bond and Kelly, 1955), but as globe size decreases the relative contributions of air temperature and velocity to the heat balance of the globe increase.

**Integrative Systems**

Many livestock production facilities exist in environments that may differ significantly from the conditions at the closest weather station. Furthermore, hot weather advisories for livestock producers using the Livestock Weather Safety Index (LWSI; LCI, 1970), related to the Temperature Humidity Index (see Chapter 5 for more detail), is no longer available over commercial radio or television broadcasts for most livestock production areas. There is a need to integrate local weather data, as collected by a dedicated weather station located at a feedlot, into a single livestock safety factor accessible to livestock producers for management decisions.

**Livestock Weather Safety Monitor**

To meet a need for the feedlot cattle industry, Eigenberg et al., (2007) used a commercial weather station to gather real-time, on-site measures of ambient temperature, relative humidity, solar radiation, and wind speed every 15 minutes. The weather station was interfaced with a microcomputer through a user-designed interface board and an output screen. The microcomputer was programmed to perform routine tasks including communications with the weather station and generating estimated cattle respiration rates (RR). The predicted respiration rate was calculated from an equation developed by Eigenberg et al (2005) based on dry-bulb temperature, dew-point temperature, solar thermal radiation, and wind speed. The equation is presented as Equation 4 on page 122 of Chapter 5. The estimated RR was related to the Temperature Humidity Index (THI). The THI stress categories (Table 5) range from normal, alert, danger, and emergency and are related to RR as developed by Eigenberg et al. (2005). The complete assembly of the Livestock Safety Monitor is shown in Figure 3. Its output displays both the predicted RR and the heat stress category.
Table 5. Heat stress categories related to predicted respiration rate of cattle (Eigenberg et al., 2005).

<table>
<thead>
<tr>
<th>Heat Stress Category</th>
<th>Predicted Respiration Rate, breaths/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>up to 90</td>
</tr>
<tr>
<td>Alert</td>
<td>90 to 110</td>
</tr>
<tr>
<td>Danger</td>
<td>110 to 130</td>
</tr>
<tr>
<td>Emergency</td>
<td>130 and higher</td>
</tr>
</tbody>
</table>

Figure 3. Livestock Safety Monitor showing commercial weather station and display unit, from Eigenberg et al. (2007).

Web Page for Cattle Heat Stress Forecasts

Until the mid 1990s, livestock producers had access to National Weather Service (NWS) livestock weather warnings through local news outlets. After this service was discontinued, producers were left to interpret weather data on their own. To fill this void, livestock weather warnings (based on the THI) were made available through several university web sites. The Livestock Safety Monitor provides an alternative approach based on a physiological-based model by Eigenberg et al. (2005) to predict the level of heat stress for unshaded cattle at temperatures above 25°C. A website was developed using the Eigenberg et al. (2005) index (Table 5). The website uses seven-
day weather forecast information, available from the NWS, to predict the intensity of summer heat events for the U.S. Central Plains region (South Dakota, Nebraska, Iowa, Western Colorado, Kansas, Missouri, Oklahoma, and Northern Texas) up to a week in advance. The prediction equation in combination with the NWS weather data is displayed as a color-coded livestock stress map with four stress categories (normal, alert, danger, and emergency) depicted across the Central Plains region. This graphical display has been available on the USMARC website since June, 2007. To access it, go to www.usmarc.usda.gov then click on Cattle Heat Stress. The results of this work provide guidance in management decisions for cattle feeding operators.

Perspectives for the Future

Future animal agriculture is likely to increasingly use sensors, electronic identification systems (ID), wireless communication, global positioning systems (GPS), etc. Sensors will need to be rugged, inexpensive, and accurate. Sensors will likely communicate with each other wirelessly providing micro and macro environmental data to smaller, more powerful computing machines. These advances will allow new concepts such as precision animal management to be developed further.

Precision management of livestock will result from integration of electronic identification (EID) and GPS systems into production management schemes to track and record individual animal performance and movement. These performance records will allow the ration, medication, and shipping history to be reviewed for each individual animal to maximize performance, health, and well-being of the herd. External information such as environmental factors and management decisions can be integrated into the individual animal’s database.

Having individual animal data presents an additional opportunity for genetic markers to be determined for specific traits. Improved genetics offers greater opportunity for animal producers to provide a safe and desirable product to consumers. Such research requires the use of large animal numbers to perform the statistical correlations. Under the evolving technology, these methods are likely to become commonplace.

References


