THEORY AND APPLICATION OF KURZ THERMAL CONVECTION MASS FLOW METERS

KURZ INSTRUMENTS INC.™

INTRODUCTION

Many versions of thermal convection mass flow meters have been made, starting in the early 1900's. Originally labeled, "hot wire" anemometers and used in laboratories for velocity profile and turbulence research, they were small, fragile and impractical devices. Generally, the sensors were operated in a constant current mode and rarely were automatically temperature compensated for temperature changes of the fluid stream. Because of their small size (less than 0.001 inch) they had a fast velocity response, but were extremely susceptible to dirt and breakage. As industrial users learned of the possible advantages of thermal convection sensors, larger and much more rugged sensors were needed for a wide variety of practical process applications. Kurz was the first to develop all-welded dual-sting sensors that have the following important features:

- **Direct mass flow measurement without the need for pressure or temperature correction**
- **High level electronic signal output**
- **Exceptional low speed sensitivity**
- **High turn-down ratio (up to 1,000:1)**
- **Nearly constant percent-of-reading accuracy**
- **Low cost, easy installation**
- **Negligible pressure drop**
- **Large temperature and pressure range**
- **Solid-state, no moving parts, shock resistant**
- **Very good repeatability**
- **Fast response to velocity and ambient temperature changes**
- **Insensitivity to non-axial velocity components**
- **Two-wire loop-powered operation**

When compared to other types of flow measuring elements, such as an orifice plate, for example, it is easy to see why thermal mass flow meters have been rapidly gaining acceptance.

As we all know, the process industry is rapidly shifting from pneumatic to electronic signals and controls. The Kurz thermal mass flow meters have the "right-stuff" to easily fit into this computer and microprocessor environment.

THEORY OF OPERATION

There are two types of thermal mass flow meters; energy balance and convection. Energy balance flow meters generally use a small diameter capillary tube having a large L/D ratio to ensure fully developed velocity and temperature profiles. The temperature of the fluid is measured at the inlet and outlet, and a constant source of heat is added to the stream. The temperature gain is a function of the specific heat of the fluid and the mass flow and follows the First Law of Thermodynamics (energy is conserved). These devices are generally used for small clean gas flows with modest flow and temperature ranges and turn-down ratios. A major use is in the semiconductor process industry.

This paper is devoted to **thermal convection** mass flow meters. In this instrument, a heated sensor is inserted into the flow stream. Since convective heat transfer is dependent on the temperature difference between the heated sensor and the fluid, a temperature sensor is incorporated into the design and is used for temperature compensation.

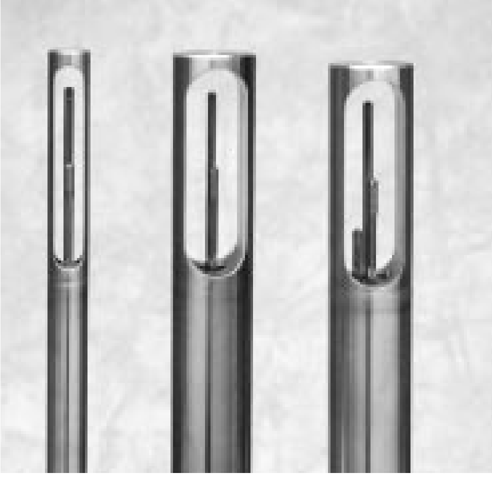

Figure 1 *– Typical Kurz All-Welded Sensors*

Two basic types of thermal convection mass flow sensor electronic circuits are in general industrial use today:

- Constant Power Anemometer (CPA)
- Constant Temperature Anemometer (CTA)

A Constant Power Anemometer (CPA) provides constant electrical power to a resistance element. A temperature sensor is attached to the heater and is heated by conduction from the heater element. The difference between the temperature of the heated sensor and the ambient fluid temperature sensor is measured. The temperature difference is large at a low velocity and small at a high velocity. The temperature difference signal is conditioned to be linear with the mass velocity. Ambient temperature compensation is usually accomplished with analog signal processing. Constant power anemometers are slow to respond to changes in velocity and temperature because of the thermal inertia of the sensors; they do not have a stable "zero" because of the increased free convection caused by the high sensor temperature at zero flow; and unless specially corrected, they have a limited range of temperature compensation (±30°F). Most CPA's use three elements to provide the power, heated sensor temperature and ambient sensor temperature, and are very sensitive to non-axial velocity components because of their non-symmetric shape.

The focus of this paper is on the Constant Temperature Anemometer. In this instrument, a single RTD sensor is operated by a solid-state feedback control circuit to maintain a constant temperature difference between the heated sensor and the process fluid temperature which is measured by a second RTD sensor. The amount of electrical power needed to maintain this temperature difference is the measured output variable. As the fluid temperature changes, the CTA control circuit maintains a constant "over-heat" temperature difference between the heated sensor and the ambient fluid temperature. The CTA circuit has a significant advantage over the CPA because it may be compensated for the temperature difference and the rate of change of the temperature difference. The CTA is the most recent method of sensor control and has been used almost exclusively for research anemometers and recent entries into the industrial market place. The CTA has several advantages over the CPA and the original "hot-wires" that used constant current. These advantages are:

- A high level output is obtained. In most cases, a power transfer ratio of 9:1 from zero velocity to 200 SFPS is obtained.
- Only two sensors are needed, rather than three as used in a CPA.

THEORY OF OPERATION continued

- CTA's have a much faster response to velocity changes than CPA's because only the outer surface of the heated element must be heated; most of the sensor is already at a constant temperature. Thus, CTA's have velocity time constant of about 1 second and are 5 to 10 times faster than their time constant as a temperature sensor. Conversely, CPA's depend on the entire sensor element mass to change temperature, and are much slower, about 15-30 seconds.
- CTA's, if properly designed, have a much smaller time constant than CPA's for fast changes in ambient fluid temperature. The CTA temperature time constant is 1-3 seconds, whereas CPA's are about 15-30 seconds.
- CTA's are much less sensitive to the angle of velocity approach because the sensors are circular; CPA's usually have two circular elements brazed side-by-side and are asymmetric, thereby being highly sensitive to rotation and yaw velocity components.

CTA SENSOR CIRCUITRY

Most CTA's use a modified Wheatstone Bridge in which the voltage difference across the bridge is amplified and fed back to the top of the bridge to maintain a constant temperature difference between the heated sensor and the temperature compensation sensor. The heated sensor is the active element in the control circuit. Kurz uses a special platinum RTD (resistance temperature detector) for both sensors. RTD's are very repeatable, essentially linear with temperature, and can be self-heated to provide a known "overheat" temperature based on their standard resistance versus temperature table. Thus, the RTD has the unique property of being a heater as well as a very accurate temperature sensor and one less element may be used compared to most CPA's in which a separate heater is required. This also allows superior flow characteristics. Years ago, Kurz recognized the need to have the mass flow element remote from the signal conditioning because of EMI, radiation, temperature or long cable length. Because of this need, Kurz introduced the loop-powered current output bridge circuit. We recognized that nearly all of the current used to heat the sensor is directly related to the total current of the bridge. The signal conditioning circuitry provides the dc power (generally +24 VDC) and through the means of a dropping resistor at the power supply return, converts the output current to a voltage which is then processed to obtain the calibrated linear 0-5 VDC and/or 4-20 mA signal. Because of the loop-powered method, extremely long distances can be used between the sensor circuit and the mass flow computer.

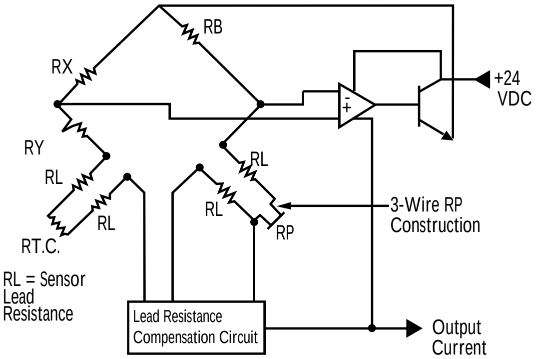

Figure 2 *– Two-wire, loop-powered CTA Bridge Circuit*

Figure 2 shows the Kurz 2-wire loop-powered sensor circuit with sensor lead length compensation. The bridge ratio is set by RX/RB and RY provides the overheat resistance reference. Kurz products use a three-wire heated sensor and a unique sensor lead resistance compensation circuit to eliminate the sensor lead length resistance effect. This circuit allows the user to shorten or lengthen the sensor lead wires without changing the calibration. In one application, the remote sensor leads are 500 feet long and the CTA output is unaffected by the change in length and temperature changes in the cable. This is an important consideration because the heated sensor has low resistance (10-20 Ohms) such that changes in the sensor lead wires, without compensation, can create a significant error in the output.

HEAT TRANSFER EQUATIONS

All objects are subject to the loss of heat by forced convection due to velocity. Wind chill is a popular demonstration of the effect that wind has on an individual, even with moderate ambient temperatures. The calculation of the heat transfer coefficient is not easy for most geometries, and is based on experimental data for the most part. In general, however, the heat transfer due to forced convection is given by:

$$Q = hA(T_S - T_\infty) \tag{1}$$

Where:

Q = Loss of Thermal energy
h = Heat transfer coefficient
T_S = Surface temperature
T_∞ = Fluid Ambient temperature
A = Area of heated element

The relationship for the forced convection heat transfer coefficient (h) for a cylinder in cross-flow follows a non-dimensional correlation as given on the next page:

HEAT TRANSFER EQUATIONS continued

(2) $N_{Nu} = C \cdot (Re)^m \cdot (Pr)^n$

Where:

N_{Nu} = Nusselt number = hd/κ
C = Constant
Re = Reynolds number = $\dfrac{\rho V d}{\mu}$
P_r = Prandtl number = $\mu C_p/\kappa$
m = Coefficient
n = Coefficient
h = Heat transfer coefficient
d = Sensor diameter
κ = Thermal conductivity of fluid
μ = Fluid viscosity
C_p = Specific heat of the fluid
ρ = Fluid density
V = Fluid velocity
ρV = Mass velocity

The Prandtl number for gases is approximately 0.7 and does not vary much with temperature, so it is generally dropped from the equations. Using equation 2, the heat transfer coefficient (*h*) is:

$$h = \frac{C\kappa}{d}\left(\frac{\rho V d}{\mu}\right)^m \tag{3}$$

Equation (1) does not include all the terms that influence a thermal mass flow sensor. At near zero velocity, free convection occurs. The heated sensor self-generates a small velocity which removes some heat from the sensor. Once forced convection takes place, the free convection becomes very small. Free convection is a buoyancy effect and is dependent on the sensor temperature. Because CPA's operate with a high temperature near zero flow, the free convection term is magnified; whereas, with CTA's the free convection term is smaller and constant for all velocities; and, therefore, allows a much more stable zero value. Generally, CTA's show an uncertainty of only ±20 feet-per-minute; which is truly exceptional, when one realizes that no other process instrument can approach this low value; certainly not a Pitot tube!

Another effect that needs to be included is the heat transfer by conduction from the heated portion of the sensor to the base of the sensor. Good design makes this effect small. Another effect is thermal radiation. We have found that this heat loss is small compared to forced convection for normal temperatures. We can combine these effects into one equation which approximates the governing equations for a thermal convection mass velocity sensor as:

$$Q = \frac{\kappa A}{d}\left[B + C\left(\frac{\rho V d}{\mu}\right)^m\right](T_S - T_\infty) \tag{4}$$

Q is the total energy loss by all mechanisms, B is a constant to account for free convection, radiation, and conduction to the sensor support structure. This equation, or versions of it, has been termed King's Law and has been used extensively for small hot wires.

One can now see why thermal convection flow sensors measure mass velocity. It is the grouping ρV that provides this convenient, direct measurement of mass flow per unit area. Thus, in the case of a CTA, a two-wire current output can be readily converted to an output proportional to mass velocity without the need for other measurements such as pressure and temperature as are needed to correct an orifice plate, Pitot tube, turbine meter, vortex meter, etc., to obtain either actual or mass velocity. This is a huge advantage for a thermal convection flow meter!

The output of a CTA has a non-zero output (live-zero) at zero flow. It means that zero is a valid calibration point for a CTA. This is very important; if an instrument doesn't zero when at zero flow, then something is wrong. Conversely, zero flow is not a good calibration point for a CPA, because of the large influence of free convection.

The coefficient, m, at least for Kurz sensors is about 0.30. This is why the CTA has unexcelled low velocity sensitivity; and a nearly equal percent-of-reading accuracy. ***Figure 3*** shows a typical calibration curve of an Kurz Metal Clad Insertion Mass Flow Element.

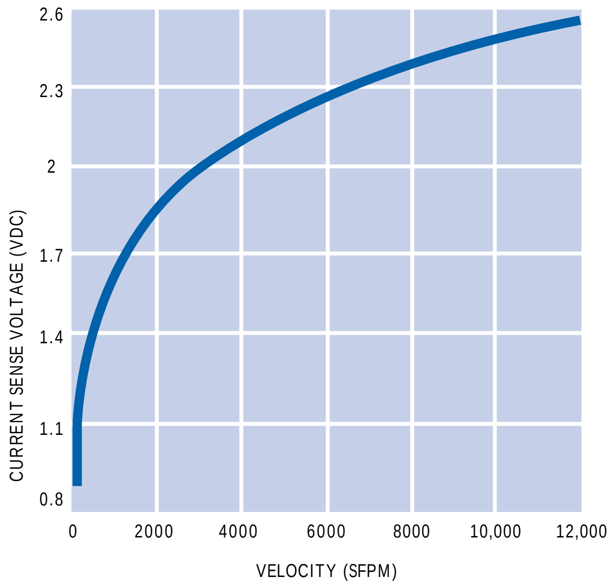

Figure 3 – *Typical Velocity Calibration Curve*

EFFECT OF FLUID PROPERTIES

The output of all thermal convective meters is dependent on the fluid properties. The most important property is the thermal conductivity and, secondly, the fluid viscosity. For accurate measurements, a calibration is usually performed with the fluid used in the application. Kurz has also developed a correlation gas calibration method to accurately predict the output for other gases based on an air calibration. This method has been extremely useful, saving time and money, and is very accurate.

TIME RESPONSE TO FLOW AND TEMPERATURE CHANGES

Figure 4 shows the response of a Kurz Fast Dual (FD) MetalClad™ sensor to a step change in velocity. Kurz manufactures the fastest industrial quality sensors available.

Figure 5 shows a typical response to a step change in temperature for a Kurz Fast Dual (FD) metal-clad sensor. It is exceptional and allows use of the sensor for combustion air flow measurement in boilers that mix hot and cold air for temperature control in coal pulverizers, for example. Note that the time constant (63%) is about one (1) second for both velocity and temperature changes. This is a huge advantage, especially over competitive CPA devices which have a time constant of 15-30 seconds!

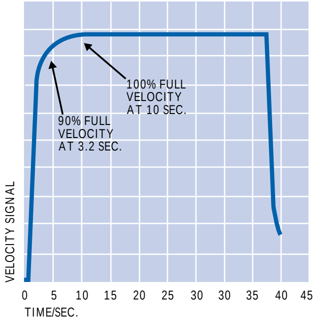

Figure 4 *– Sensor Flow Response*

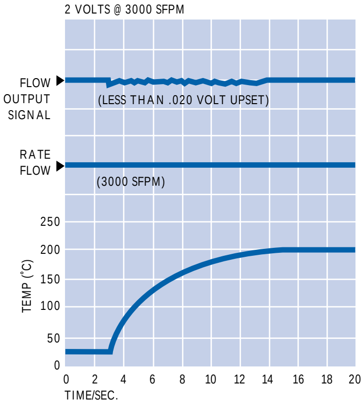

Figure 5 *– FD Sensor Temperature Response.*

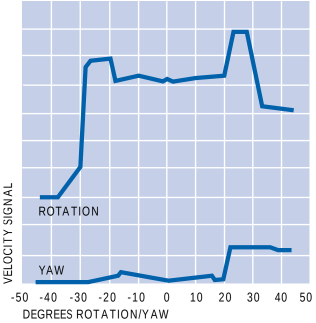

Figure 6 *– Sensor Measurement Error versus Rotation/Yaw Alignment Angles.*

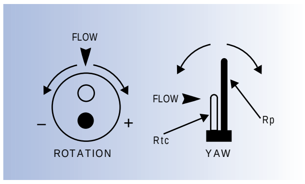

Figure 7 *– Sensor Rotation and Yaw Alignments.*

ORIENTATION EFFECTS

Figure 6 shows a typical output response to changes in the incoming velocity direction. Data is shown for rotation and yaw, as defined by ***Figure 7.*** Note that the effect is small for angles up to ±20 degrees. This is extremely important for flow applications having severe turbulence and a non-axial velocity direction. Competitive CPA devices must be lined up within ±2° which is a severe disadvantage.

TYPES OF KURZ THERMAL CONVECTIVE MASS FLOW ELEMENTS

Kurz offers three types of thermal mass flow elements:

a) In-line Mass Flow Elements (Kurz Series 502, 510, 522 UHP, 532, for example).

b) Single-Point Insertion Mass Flow Elements (Kurz Series 452, 410, for example).

c) Multi-Point Insertion Mass Flow Elements (Kurz K-BAR 24, for example).

IN-LINE MASS FLOW ELEMENTS are generally used for small pipes and in situations in which a higher accuracy is required. These are designed to include the proper upstream and downstream dimensions, screens and nozzles as appropriate, so that the mass velocity profile within the in-line flow element is flat and invariant. ***Figure 8*** shows a Kurz Series 502 In-Line Flow Element with a Model 155 Jr Mass Flow Computer.

Figure 8 *– Series 502 In-Line Mass Flow Element and 155Jr Mass Flow Computer.*

SINGLE-POINT INSERTION MASS FLOW ELEMENTS measure the velocity at the point in a duct or stack in which they are inserted. Therefore, the user's duct serves as the flow body and the output is dependent on the relationship between the average velocity and the measurement location velocity. For pipes larger than about 2-1/2 inches, a single point insertion mass flow element is generally used because of its simplicity and lower cost. These units are very attractive as they can easily be inserted under flowing conditions ("hot-tapped") and are very versatile. ***Figure 9*** shows a Kurz Series 452 Insertion Mass Flow Element with a Model 155Jr Mass Flow Computer. For maximum accuracy an in-situ mass flow calibration is usually performed over the operating range of velocities and variable velocity correction factors are entered into the Series 155 Mass Flow Computer.

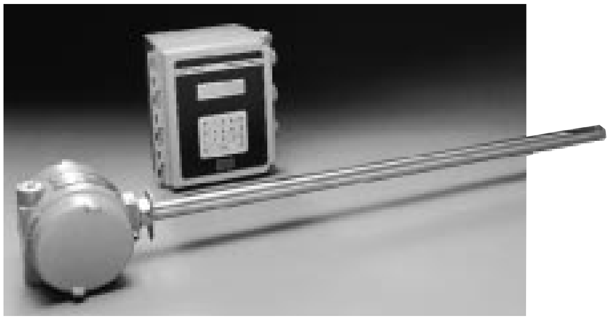

Figure 9 *– Series 452 Insertion Mass Flow Element and Model 155Jr Mass Flow Computer.*

MULTI-POINT INSERTION MASS FLOW ELEMENTS are used in larger ducts in which each sensor is placed at an equal area location in the duct, pipe or stack. ***Figure 10*** shows a Kurz K-BAR 24 Multi-Point Mass Flow Element and Series 155 Mass Flow Computers. Again, for maximum accuracy an in-situ calibration is recommended.

A recent development is the "Puffer Probe" which includes an automatic sensor cleaning system using compressed air. It is offered with both types of Insertion Mass Flow Elements.

Figure 10 *– K-BAR 24 Multi-Point Mass Flow Element and Series 155 Mass Flow Computers.*

MASS FLOW COMPUTERS

In the last few years, large advances have been made in using microprocessor technology to provide versatile signal conditioning and output functions for a wide variety of instruments. The Kurz Series 155 Mass Flow Computers operate most Kurz products. The microprocessor serves as a flow computer incorporating the sensor calibration, duct area, sensor diagnostics, display, outputs, variable velocity correction factors, redundancy, etc.

Key features of the Kurz Series 155 Mass Flow Computers include:

- Multiple flow or temperature sensor inputs.
- Flow totalizers for each Meter.
- Keyboard selectable calibration range.
- Selectable flow area.
- Selectable output signal dampening.
- Selectable alarms, relay outputs.
- System self-diagnostics.
- Selectable variable velocity correction factors.
- User friendly help screens.
- Built-in operator keyboard and display.
- Selectable engineering units (English and Metric).
- Selectable unit ID.
- Password protection.
- 24-hour clock and calendar.
- Easy input calibration; i.e., all digital (no pots).
- Digital communications, RS 232C, RS 485.
- System firmware configuration Upload/Download from an IBM compatible personal computer.
- Automatic sensor out-of-calibration and detection and reaveraging for multi-sensor flow elements (Flow Perfect™) allowing system redundancy.
- Automatic Electronic "Zero and Span" drift check as required by EPA for Stack Flow Monitors.
- Velocity-Temperature Mapping (VTM) in which software techniques are used to improve temperature compensation from 0°C to 500°C over the full velocity range.

APPLICATIONS

Over the past 20 years, Kurz thermal convection mass velocity meters have been used successfully in most flow applications and have become the instrument of choice for many of them. Typical applications include:

- Process Gas measurements in Chemical and Petrochemical plants (These generally require hazardous location approvals).
- Combustion air measurement for large utility boilers, co-generation plants, and other combustion processes.
- Mass flow measurements for stack effluent monitoring and incinerators.
- Aeration air, digester and chlorine gases in municipal waste water treatment plants.
- Semi-Conductor process gas measurements and control, including Ultra-High Purity gases.
- HVAC applications involving ventilation and temperature control.
- Air Sampling in Nuclear Power Plants and DOE facilities.

CONCLUSION

Kurz rugged, industrial grade "Smart" thermal convection mass flow elements and mass flow computers are making a large impact on flow measurement technology. Their use will grow rapidly as they allow convenient solutions to difficult applications and displace traditional technologies. Fast response, simple installation, electrical output, large turn-down ratio, and dirt insensitivity make the Kurz thermal convection mass flow meters a competitive alternative to conventional flow meter technology for many important applications. Please contact Kurz Instruments or our representatives for detailed information on Kurz mass flow products.

OUR MISSION

To manufacture and market

the best thermal mass flow meters

available and to support our

customers in their efforts to

improve their business.

KURZ™
INSTRUMENTS INC.

The leader in Mass Flow

Technology for Process and

Environmental Measurement