**Reactor Engineering
Division**

by R. J. Page

FEB 05 1997

OSTI

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

MASTER

Argonne National Laboratory, Argonne, Illinois 60439
operated by The University of Chicago
for the United States Department of Energy under Contract W-31-109-Eng-38

Reactor Engineering
Division
Reactor Engineering
Division
Reactor Engineering
Division

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Modeling and Testing of a Thermal Transient Anenometer

by

Richard J. Page

October 1996

Argonne National Laboratory
Reactor Engineering Division
9700 South Cass Avenue
Argonne, IL 60439

TABLE OF CONTENTS

	<u>Page</u>
1.0 INTRODUCTION	1
2.0 THEORY OF OPERATION OF THE TTA	1
3.0 COMPUTER MODEL OF THE TTA	2
3.1 Model Description	2
3.2 Model Input Parameters	5
4.0 EXPERIMENTAL FLOWBENCH	7
5.0 RESULTS	7
5.1 Method of Calculation	7
5.2 Results of the 0.040 in. probe	9
5.2.1 Air velocity = 4 m/s	9
5.2.2 Air velocity = 16 m/s	13
5.3 Results for the 0.063 in. probe	16
5.3.1 Comparison with the 0.040 in. probe results	16
5.3.2 Air velocity = 16 m/s	18
5.3.3 Air velocity = 4 m/s	18
5.4 Comparison of Current Results with Previous Heat Transfer Data	20
6.0 SUMMARY OF RESULTS FOR THE TTA PROTOTYPE	20
7.0 INVESTIGATION OF NEW PROBES	22
7.1 Description of new probes	22
7.2 Results for the SP1 probe	22
7.3 Results for the SP2 probe	27
7.4 Correlation of SP1 and SP2 results	27
8.0 EFFECT OF AXIAL HEAT CONDUCTION	32
9.0 CONCLUSIONS	36
10.0 REFERENCES	38

LIST OF FIGURES

<u>No.</u>		<u>Page</u>
Fig. 1.	Heat Transfer from the Transient Thermal Anemometer	3
Fig. 2.	SINDA Model of the TTA	4
Fig. 3.	Typical Cross-Section of SINDA Model	6
Fig. 4.	Effective Conductivity of MgO and Air	8
Fig. 5.	TTA Model Calculation for .040 in. Probe, V=4 m/s	10
Fig. 6.	Calculation of Slope for .040 in. Probe, V=4 m/s	11
Fig. 7.	Comparison of Model with Data, .040 in. Probe, V=4 m/s	12
Fig. 8.	Comparison of Model with Data, .040 in. Probe, V=16 m/s	14
Fig. 9.	Calculation of Slope, .040 in. Probe, V=16 m/s	15
Fig. 10.	Comparison of Model with Data, .063 in. Probe, V=4 m/s	17
Fig. 11.	Comparison of Model with Data, .063 in. Probe, V=16 m/s	19
Fig. 12.	Heat Transfer Characteristics - Present Investigation Compared with Literature Results	21
Fig. 13.	Comparison of Model with Data, SP1 Probe, V=2 m/s	23
Fig. 14.	Comparison of Model with Data, SP1 Probe, V=8 m/s	24
Fig. 15.	Comparison of Model with Data, SP1 Probe, V=16 m/s	25
Fig. 16.	Slope vs. Time for SP1 Probe	26
Fig. 17.	Comparison of Model with Data, SP2 Probe, V=2.5 m/s	28
Fig. 18.	Comparison of Model with Data, SP2 Probe, V=8.6 m/s	29
Fig. 19.	Comparison of Model with Data, SP2 Probe, V=16 m/s	30
Fig. 20.	Slope vs. Time for SP2	31

LIST OF FIGURES (cont'd)

<u>No.</u>		<u>Page</u>
Fig. 21.	Slope vs. Convective heat transfer coefficient for SP1 and SP2 Probes	33
Fig. 22.	Slope vs. h/d for SP1 and SP2	34
Fig. 23.	Log Nu vs. Log Re for SP1 and SP2	35
Fig. 24.	Slope vs. Time for various insulated lengths of probes	37

EXECUTIVE SUMMARY

The Thermal Transient Anemometer (TTA) is a fluid mass flow measuring device which utilizes a thermocouple as a probe. The probe is periodically heated by an electric current pulse through the thermocouple junction, and the measured rate of cooling between pulses is related to the local mean flow velocity. The standard thermocouple sensor provides an inexpensive flow probe which is durable, rugged, and capable of satisfactory operation in hostile environments.

The TTA was developed and patented in prototype form by Instrument Development for Applied Physics (IDAP), a small U.S. company. IDAP has tested the TTA and shown that the measurement principle is valid. However, there is a need to refine the prototype so that the TTA becomes a commercially viable instrument. The main concern is to reduce the heating current to the TTA so that battery-powered operation is possible. To do this, a probe needs to be developed such that only the region local to the thermocouple junction is heated, rather than the entire length of the wire. There are a number of ways that this might be done, and IDAP has worked with ARi Industries, a thermocouple manufacturer, to develop probe designs that would have this characteristic, and at the same time would retain the ruggedness and ease of manufacture of a standard thermocouple. The purpose of this CRADA (#FWP 73430) was to investigate these designs with a view to their possible commercial development.

The starting point was to develop a computer model of the TTA as it currently exists, i.e., the prototype configuration, and to compare the results with experimental data. Good agreement between model and data was obtained, thus allowing new designs to be analyzed with some confidence.

Two new locally heated probes were modeled. It was found that one of the probes was superior to the other with respect to power requirements and time of response. It was also determined that axial heat conduction plays a significant role in the response of these probes. It is important that the heated part of the probe be completely in the flow stream being measured, and that the non-heated part of the probe be insulated.

1.0 INTRODUCTION

The Thermal Transient Anemometer (TTA) is a fluid mass flow measuring device which utilizes a thermocouple as a probe. The probe is periodically heated by an electric current pulse through the thermocouple junction, and the measured rate of cooling between pulses is related to the local mean flow velocity. The standard thermocouple sensor provides an inexpensive flow probe which is durable, rugged, and capable of satisfactory operation in hostile environments.

The TTA was developed and patented in prototype form by Instrument Development for Applied Physics (IDAP), a small U.S. company. IDAP has tested the TTA and shown that the measurement principle is valid. However, there is a need to refine the prototype so that the TTA becomes a commercially viable instrument. The main concern is to reduce the heating current to the TTA so that battery-powered operation is possible. To do this, a probe needs to be developed such that only the region local to the thermocouple junction is heated, rather than the entire length of the wire. There are a number of ways that this might be done, and IDAP has worked with ARi Industries, a thermocouple manufacturer, to develop probe designs that will have this characteristic, and at the same time will retain the ruggedness and ease of manufacture of a standard thermocouple. The purpose of this CRADA is to investigate these designs with a view to their possible commercial development.

The starting point was to develop a computer model of the TTA as it currently exists, i.e., the prototype configuration. Results from this analysis were compared with experimental data in order to verify the model. The model was then modified to the configurations of the new designs, and analysis of these gave an indication of their performance.

This report describes the computer model of the TTA prototype, compares the computer analysis with prototype experimental data, and investigates the characteristics of two new designs.

2.0 THEORY OF OPERATION OF THE TTA

The theory of operation of the TTA is given in Reference 1. Briefly, the temperature decay of a thermocouple junction a short time after a heating pulse can be represented by:

$$T(r,t)=A \exp(-ka^2t)$$

where A is a constant for fixed initial conditions, flow conditions, and radial position r; and a is the smallest eigenvalue of the solution to the general heat transfer equation.

When this is plotted on a semilogarithmic plot, one obtains a straight line, i.e., a constant temperature decay slope given by:

$$S=-ka^2=\ln(T_2/T_1)/(t_2-t_1) \quad (1)$$

The initial conditions do not enter into this expression and therefore the slope is independent of the power pulse shape, magnitude and duration.

For the case where the internal thermal resistance is small compared with the external resistance, which is typical for air flows, it can be shown that:

$$\ln(T_2/T_1)/(t_2-t_1)=-hA/\rho CV$$

where h is the external heat transfer coefficient, ρC is the heat capacity of the probe, A is the surface area, and V is the volume. From here, using the heat transfer correlation for a cylinder in a cross-flow (Ref. 2):

$$Nu=CRe^n$$

one obtains a relationship of the form:

$$S=-4C*[\text{probe properties term}]*[\text{fluid properties term}]*V^n$$

where V is the fluid velocity.

Thus, the constant slope S of the semilogarithmic temperature decay after the heating pulse is a measure of the local fluid velocity. This is the operating principle of the TTA.

3.0 COMPUTER MODEL OF THE TTA

3.1 Model Description

The TTA was modeled using the SINDA heat transfer code. SINDA is a finite difference code that solves both transient and steady state problems. The TTA model is a three-dimensional, time-dependant calculation that involves internal heat generation and heat conduction, and external heat convection. A sketch of the prototype TTA, indicating these heat transfer mechanisms, is shown in Figure 1.

Figure 2 shows the prototype model geometry, which is an approximation of Figure 1. Axially, there are four distinct regions: (1) the steel end cap is modeled as a cylinder rather than a hemisphere. The length of the cylinder was adjusted so that both the volume and surface area were close to that of the hemisphere; (2) the region between the end cap and the thermocouple junction. This is a steel cylinder filled with magnesium oxide (MgO); (3) the junction was modeled as a sudden change in area, with the bead itself having a diameter of one of the wires; and (4) the rest of the probe, consisting of an outer steel cylinder with an MgO insert, and thermocouple wires running through the MgO.

Fig. 1. Heat Transfer from the Transient Thermal Anemometer

G11202

Fig. 2. SINDA Model of the TTA

A typical cross-section of the model is shown in Figure 3. To improve computer running time, symmetry about both the radial axes was assumed. This is not strictly correct since the thermocouple wires, being of different materials, will have different heating characteristics and thus one would not expect a perfectly symmetric temperature distribution in the probe. Also, the heated wire was modeled as an arc segment rather than a half-cylinder. The cross-sectional area of the arc segment was made equal to that of the wire half-cylinder.

3.2 Model Input Parameters

The model geometry was described in the previous section. However, to obtain results from the computer model other parameters must be specified. These are:

(1) the convective heat transfer coefficient at the outer surface of the probe. This can be approximated, and used as a first estimate, by using the well-known correlation for heat transfer from a heated cylinder in cross-flow:

$$Nu_d = K \times Re_d^n \times Pr^m$$

where K and n depend on the Reynolds number range, and m is a constant.

(2) The properties of the magnesium oxide. The manufacturer (ARi Industries) states that the effective density of the MgO in their thermocouples is 72%. This enables the heat capacity, ρC_p , and thermal conductivity, k, to be estimated. The density is simply 0.72 times the value for 100% dense MgO, which is well known, and C_p is likewise well known. However, the thermal conductivity of porous media such as MgO is less certain. In this configuration, we can consider the material to be a mixture of 100% dense MgO and air. According to Bauer (Ref. 3), for the case where the conductivity of the solid is much greater than that of the gas, and where the gas phase predominates, the thermal conductivity of the porous material can be approximated by the expression:

$$k = k_g \times \left(\frac{V_g}{V_g + V_s} \right)^{-3} \quad (2)$$

where k_g is the conductivity of the gas, V_g is the volume fraction of the gas, and V_s is the volume fraction of the solid.

On the other hand, when the volume fraction of the gas is low (below about 0.3), and the solid part of the mixture is predominant, the thermal conductivity k can be calculated from (Ref. 4):

Fig. 3. Typical Cross-Section of SINDA Model

$$\frac{1 - (\frac{k_s}{k})}{2 + (\frac{k_s}{k})} + \frac{1 - (\frac{k_g}{k})}{2 + (\frac{k_g}{k})} \times \frac{V_g}{V_s} = 0 \quad (3)$$

where k_s is the thermal conductivity of the solid. This equation represents a compromise between the "gas continuous" medium of Equation 2 and the corresponding "solid continuous" medium.

The problem is that, as shown in Figure 4, Equations 2 and 3 give very different results. We therefore need some rationale for using one or the other. This issue is addressed later on.

(3) The third input parameter is the value of the heat generation rate per unit volume, q . This can be calculated from measurements of the resistance of the wires and the applied current, and an estimate of the wire cross-sectional area and length, thus:

$$q = \frac{I^2 \times R}{a \times l} \quad (4)$$

where I is the current, R is the resistance of the wires, a is the cross-sectional area of each wire, and l is the total length of both wires. Due to uncertainties in these measurements, especially I and a , the value of q so calculated is considered a first approximation.

4.0 EXPERIMENTAL FLOWBENCH

Experimental data were obtained in air at the exit plane of a round nozzle. An instrumented sharp-edged ASME orifice was located in the duct upstream of the nozzle to provide a measured flow rate. Fans provided a maximum air velocity of about 16 m/s.

5.0 RESULTS

5.1 Method of Calculation

Experimental data were available for 0.040 in. and 0.063 in. diameter probes, in air flows of between 4 and 16 m/s. Therefore, these were the configurations modeled. We first considered the 0.040 in. diameter probe. Given that the geometry of the probe was already modeled, the next steps were as follows:

Fig. 4. Effective Conductivity of MgO and Air

- (i) Calculate the heating rate from Equation 4 and measured value of I.
- (ii) Calculate the external heat convection coefficient from the measured flow velocity
- (iii) Assume, to begin with, that the MgO was 72% dense everywhere in the probe, and that the solid part was predominant so far as heat conduction was concerned, i.e., it was "solid continuous." Calculate k from Equation 3.
- (iv) Run the SINDA code with these values and compare the results with the data.
- (v) Adjust q, h, and k within a range of defensible values to obtain a best fit with the data.

The parameter to be calculated, and compared with data, is ΔT , the difference between the temperature measured by the thermocouple probe and ambient. This parameter is plotted against time in order to get the rate of temperature decay as the probe cools after the applied electrical pulse is removed, and hence the slope S. The TTA works on the principle, as explained previously, that this slope becomes invariant with time after a short initial period, and is proportional to the fluid velocity over the probe. A comparison of the slope obtained from data and from the model is therefore essential for a verification of the model. However, valuable information can be obtained by comparing the ΔT s for all times after the pulse is removed. There is no data for the heatup period, due to an unavoidable limitation in the data recording system.

5.2 Results for the 0.040 in. probe

5.2.1 Air velocity = 4 m/s

Model results for the 0.040 in. probe are shown in Figure 5 for all times, including the heatup period. In this case the probe was heated for 2 seconds. The nominal air velocity was about 4 m/s, and the heating rate is roughly equivalent to an applied current of 1.6 amps. When looking at this plot, it is important to note, since this has a bearing on what comes later, the shape of the decay curve just after the current is removed. ΔT decreases slowly at first, and then increases to a maximum decay rate at about 4 seconds before starting to level off a little.

The temperature decay slope, as defined by Equation 1, is shown in Figure 6, for times after removal of the heating current. Two things should be noted: First, for a short time the slope has a positive value, indicating that the temperature at the thermocouple sensor is increasing even though there is no heating current. This is due to heat being conducted axially along the probe to the sensor region. Second, the slope becomes substantially constant about 2 seconds after removal of the current, as predicted by theory.

Figure 7 compares the result of Figure 5 with data from the flowbench. It can be seen that the agreement is excellent every where except close to the beginning of the cool-down, and even there the difference between the model and data is small. This is a gratifying result, but it must be realized that this good agreement was achieved by judicious adjusting of the "free" parameters, q and h. On the other hand, this adjustment of parameters was not done blindly, but with consideration of the experimental conditions, as follows:

Delta T vs Time
V=4 m/s MgO Density=72% for all nodes

Fig. 5. TTA Model Calculation for .040 in. Probe, V=4 m/s

Slope vs Time
V=4 m/s MgO Density=72% for all nodes

Fig. 6. Calculation of Slope for .040 in. Probe, V=4 m/s

Fig. 7. Comparison of Model with Data, .040 in. Probe, V=4 m/s

First, the air velocity was 3.63 m/s, which gives a Reynolds Number of 235. The convective heat transfer coefficient that best fit the data was 0.0197 w/sq.cm-K, which implies a Nusselt Number of 7.974. McAdams (Ref. 5) gives a compilation of data for heat transfer from heated cylinders in cross-flow, a configuration that is similar, but not identical, to the TTA. The Reynolds Number-Nusselt Number combination derived from the model results of this investigation is very close to the "best fit" curve that McAdams draws through his published data (as shown by Figure 14 which will be discussed later).

Second, the heating rate q that gave good agreement between data and model was 2230 w/cu.cm. We can now use Equation 4 to calculate the current that corresponds to this heating rate, and compare it with the measured current. The length of the thermocouple wire was measured to be 61.6 cm. Its resistance was measured to be 12.8 ohm. We do not have a measurement of the diameter of the wire, and besides it is not absolutely constant along its length. However, according to the manufacturer, 0.016 cm is reasonable. Putting these values in Equation 4, we get that the heating current is 1.47 amps. In fact, values between 1.6 and 1.7 were measured. Since this difference can easily be accounted for due to uncertainty in the diameter of the wire, we can be confident that a heating rate of 2230 w/cu.cm is reasonable.

In conclusion, it is shown that the values of the "free" parameters, q and h , that were input to the model to achieve good agreement with data are physically feasible and defensible.

It should be noted that the density of the MgO was assumed to be the manufacturer's value of 72%, every where in the probe, and its thermal conductivity was calculated from Equation 3. This equation assumes that heat is conducted through the material mainly by the solid particles of MgO rather than by the air trapped in between the particles. This is a crucial assumption, in that although the model results are not too sensitive to the MgO density (i.e. it makes little difference whether the assumed density is 72% or 77%), it clearly makes a big difference whether the material is "solid continuous," the upper curve in Figure 4, or "gas continuous," the lower curve, or something in between, Equation 3, since the conductivity varies by orders of magnitude. This will later be shown to be an important consideration.

5.2.2 Air velocity = 16 m/s

Figure 8 shows the comparison between data and model results with the 0.040 in. probe and an air velocity of about 16 m/s. Again, the agreement between data and model result is very good. The temperature decay slope is shown in Figure 9. It has the same general form as the 4 m/s result, but does not reach a positive value. This indicates that, although there is heat transferred axially towards the thermocouple sensor, more heat is transferred away, both axially and radially. The slope takes about 2.5 seconds to reach a near-constant value, a little longer than it did at the lower velocity.

To get this result, the heating rate q was kept the same as it was for the 4 m/s case. This is reasonable since there was no apparent change in the applied current. The MgO density and its properties were kept the same, since we were using the same probe. The convection coefficient, h , was scaled up to account for the increased velocity. The resulting excellent agreement between model results and data again gives us confidence in the model.

Delta T vs Time
V=16 m/s MgO=72% for all nodes

Fig. 8. Comparison of Model with Data, .040 in. Probe, V=16 m/s

Fig. 9. Calculation of Slope, .040 in. Probe, V=16 m/s

5.3 Results for the 0.063 in. probe

5.3.1 Comparison with the 0.040 in. Probe Results

The 0.063 in. probe was a standard thermocouple, constructed in the same way as the 0.040 in. probe. Given that, it appeared reasonable to expect that the three "free" parameters, q , h , and MgO density, would be similar except that h would be factored to account for the increased diameter, and q would reflect the measured heating current. In addition, new information regarding the geometry of the thermocouple was received from ARi at about this time, affecting the size of the junction and its position relative to the end cap. This information was incorporated into the model.

A comparison of the model output with data showed excellent agreement except in the period immediately after the heating current was removed. Here, it was found that the data had a higher maximum temperature, and an initially slower decay rate, as shown in Figure 10. A potential explanation for this behavior may be found in the way that the thermocouples are manufactured.

Essentially, the process is as follows: (1) Thermocouple wire is fed through a pair of holes in a MgO rod; (2) This rod is then inserted into a stainless steel sheath; (3) The whole assembly, which is many feet long, is put through a press so that the sheath is reduced to the desired diameter and the wires and MgO rod are firmly held inside the sheath; (4) The assembly is cut to the right length for the thermocouple (one assembly makes many thermocouples). At this stage, the wires, MgO, and sheath are all flush with one another at the end; (5) A small hand-held sand-blaster is used to remove MgO from around the wires at one end; (6) The exposed wires are welded together to form the thermocouple junction; (7) Loose MgO powder is poured around the junction, and packed down by hand using a tamper; (8) A stainless steel end-cap is welded on.

Given this method of manufacture, it is certainly feasible that the density of the MgO surrounding the junction is different from that in the bulk of the thermocouple. Not only that, it is likely that, although the bulk of the MgO is a porous material whose conductivity is governed by Equation 3, the MgO around the junction is in the "air continuous" category and so follows the lower curve of Figure 4. The difference in the thermal conductivities of these categories is about a factor of 100. To back up this assertion, we look to Bauer (Ref. 3) where experimental data is presented that shows that when loose powder is poured into a container the resulting solid density is around 60% and that the thermal conductivity does indeed follow the "air continuous" model. The MgO around the thermocouple junction is in fact poured in, and only lightly packed down. If it is assumed that this low density MgO exists from the end cap to just behind the junction, Figure 10 shows that a somewhat better agreement with the data is obtained, especially with respect to the maximum temperature.

If this is really the explanation, though, why did we not see the same behavior in the 0.040 in. probe? After all, it was made the same way. There are a number of possible reasons:

(1) The sandblasting operation which removes solid MgO from around the junction wires is not done with any precision. The depth to which the MgO is removed is not a manufacturing parameter, beyond the visual inspection to show that enough of the wires have been exposed. The

Delta T vs Time
V=4 m/s, .063 in. probe

Fig. 10. Comparison of Model with Data, .063 in. Probe, V=4 m/s

extent of this excavation, and the subsequent filling with MgO powder, may have a significant effect on the response of the sensor.

(2) As indicated by Figure 4, the transition from "air continuous" thermal conductivity to that governed by Equation 3 could occur within a narrow band of MgO density. It is feasible that since the tamping down of the powder is not a controlled process, either one of these conductivities could exist, resulting in different responses.

(3) The manufacturer states that when the wires are welded into a junction, they often "burn back" to the solid MgO. It seems that it is the relatively high thermal conductivity of the solid MgO that causes the axial conduction effect exhibited by the 0.040 in. probe. The closer the junction is to this high conductivity material, the more pronounced the effect is likely to be.

It is important to note that although the initial response of the TTA appears to be affected by such factors as heating rate, MgO density, and geometry, the later response depends only on the heat transfer from the probe. This is shown by both the model and the experimental data and is an important confirmation of the working principle of the instrument.

5.3.2 Air velocity = 16 m/s

The good agreement between model results and data is shown in Figure 11. It was obtained by making the following assumptions: (1) The MgO was excavated and refilled with low conductivity powder to just behind the thermocouple junction. Given the manufacturing technique, this is reasonable; (2) The heating rate was 1879 w/cu.cm, implying a current of 3.71 amps. This is based on an average wire diameter of 0.0278 cm, provided at ARi. The experimental measurement was 3.6 to 3.75 amps; and (3) the convective heat transfer coefficient was 0.0270 w/sq.cm-K. This implies a Nusselt Number of 17.2 to go with the Reynolds Number of 1610. This pair of numbers is consistent with the data for heat transfer from heated cylinders summarized by McAdams (Ref. 5).

Thus the values of the input parameters necessary to obtain agreement between model results and data are all consistent with experimental observations and manufacturing practice.

5.3.3 Air velocity = 4 m/s

We now needed to adjust the model parameters so that the results at 4 m/s were in agreement with experimental data. However, since the same probe was used as for the 16 m/s case, the MgO density distribution could not be changed. Restrictions were also placed on the other two parameters. The heating rate had to be consistent with observed values of current, and the heat transfer coefficient had to be within the range of McAdam's data.

The result is shown in Figure 10. The agreement with data is not as good as it was for the 16 m/s case, but is still acceptable. The heating rate of 1833 w/cu.cm implies a current of 3.66

Delta T vs Time
V=16 m/s, .063 in. probe

Fig. 11. Comparison of Model with Data, .063 in. Probe, V=16 m/s

compared with measured values of between 3.6 to 3.75. The heat transfer coefficient of 0.0120 w/sq.cm-K gives a Nusselt Number of 7.650, and the Reynolds Number (for $V=3.62$ m/s) was 369. This result is very close to the "best fit" curve quoted by McAdams.

5.4 Comparison of Current Results with Previous Heat Transfer Data

There have been many experimental investigations of the heat transfer from a heated cylinder to a fluid flowing across the cylinder. Many of these data have been assembled by McAdams (Ref. 5), in the form of a plot of Nusselt Number against Reynolds Number. The operation of the TTA is similar to these experimental configurations, in that there is internal heating and external heat transfer. There are some differences: (1) The previous experiments heated the whole length of the cylinder, except perhaps for insulated regions at the ends; (2) the cylinders were uniformly heated, at least that was the intent, whereas the TTA is unheated at one end. Also, the TTA, because of the different materials of the thermocouple wires, does not have a completely uniform temperature distribution; (3) The cylinders were continuously heated, so that the surface temperature was kept constant, and the heat transfer coefficient was estimated from a measurement of the power input, i.e., from $Q = hA\Delta T$. The TTA was heated initially and then allowed to cool, and the rate of cooling was determined by the heat transfer coefficient.

Nevertheless, the geometry and process are close enough that one would expect similar heat transfer characteristics. Figure 12 indicates that this is so. The curve is McAdams "best fit" to the accumulated data that he published. The data points were obtained from this investigation, for the 0.040 in. and 0.063 in. diameter probes, and flow velocities of about 4 and 16 m/s. It is clear that there is good agreement. When compared with the data in McAdams, the present results are well within the experimental scatter.

6.0 SUMMARY OF RESULTS FOR THE TTA PROTOTYPE

1. The computer model of the TTA gave results that are in good agreement with experimental data from the prototype TTA, and can therefore be used with confidence in the assessment of advanced designs.
2. The heat transfer characteristics deduced from the comparison of model results with data are in good agreement with data published in the literature, which further bolsters confidence in the model.
3. It was shown that the method of manufacturing the thermocouples used in this investigation can have an effect on the initial response of the TTA, in that both geometry and thermal conductivity of the MgO cannot be closely controlled. However, these factors do not affect the later response of the instrument, which is what is used to determine flow rate.

Nu-Re Correlation Heated Cylinders in Cross-Flow

— Data from McAdams x TTA Dia = .040 in. □ TTA Dia = .063 in.

Fig. 12. Heat Transfer Characteristics - Present Investigation Compared with Literature Results

7.0 INVESTIGATION OF NEW PROBES

7.1 Description of new probes

The first part of this program involved modeling a prototype TTA sensor which was constructed from a standard thermocouple, and verifying the model by comparing its results with experimental data. With a verified model, attention was then turned to the investigation of the characteristics of two new designs.

Both of the new sensors were intended to reduce the required heating current by designing them so that only a local region near the thermocouple junction was heated.

A brief description of these probes, designated SP1 and SP2, follows:

SP1---a 0.125 in. diameter probe, made from a standard thermocouple, but swaged down at one end to 0.063 in. The thermocouple wires in the swaged down end were also reduced in diameter, so that most of the heating took place at this end.

SP2---a 0.040 in. diameter probe, using a standard thermocouple sheath and wires, but incorporating a third heater wire, made of inconel, at one end. This wire was about 0.5 in. long. The heating current was applied to the heater wire only, thus providing local heating.

The computer model was revised to reflect both these designs.

7.2 Results for the SP1 probe

The model for SP1 included the transition region from .063" diameters to 0.125" diameter, and a portion of the 0.125" diameter section. MgO density was assumed to be 77% in the swaged down part and 72% elsewhere. The model was run for air velocities of 2.42, 8.6, and 15.97 m/s and the results were compared with the corresponding experimental data.

This comparison is shown in Figures 13, 14 and 15. The heating rate q and the convection coefficient h were adjusted until a good fit was obtained with the data. It can be seen that good matches with temperature decay and with the maximum temperature were obtained. In addition, it is clear that the initial response of the probe is very much a function of the flow velocity, and this trend is correctly modeled.

The heating rate in all cases was about 1700 w/cm^3 . With a measured resistance of about 2 ohms, this corresponds to a heating current of about 3.1 amps which, although lower than for a straight 0.063" sensor, is still higher than anticipated. The reason appears to be that the larger, 1/8" section of the probe acts as a heat sink, drawing heat away from the junction and requiring a larger power input. This can be inferred from the SINDA model results shown in Figure 16, which compares the response of SP1 with a straight 0.063" probe. The slope for SP1 is larger (more

Delta T vs Time
Sp-1, V=2 m/s

Fig. 13. Comparison of Model with Data, SP1 Probe, V=2 m/s

Fig. 14. Comparison of Model with Data, SP1 Probe, V=8 m/s

Fig. 15. Comparison of Model with Data, SP1 Probe, V=16 m/s

Slope vs. Time
New probe, .063 to .125 in. dia

Fig. 16. Slope vs. Time for SP1 Probe

negative), showing that the temperature of the heated section is decaying faster. In addition, it is seen that it takes the SP1 probe longer to reach a constant slope. This latter characteristic means that the time response of the instrument is increased with respect to the prototype.

To summarize the SP1 results, (1) the power requirement of the sensor was reduced, but not by as much as anticipated; and (2) the time response of the instrument was increased with respect to the prototype. For these reasons, it was concluded that the SP1 design did not represent an improvement over the prototype.

7.3 Results for the SP2 probe

The SP2 model assumed that the two thermocouple wires, and the inconel heating wire, were welded into the end cap. It was also assumed that the MgO density was 72%, i.e., nominal, throughout. The model was run for air velocities of 2.5, 8.6 and 16.0 m/s and the results were compared with the corresponding experimental data.

Figures 17, 18 and 19 show this comparison. It is seen that excellent agreement between data and model results can be obtained at all times through adjustment of q and h . Again, the initial response seems to be a function of air velocity, and this response is well modeled. It is interesting that the initial response of SP2 is quite different from that of SP1.

The heating rate was about 8500 w/cm^3 , which seems high numerically, but is only applied to the short length of inconel. This corresponds to a heating current of about 1.5 amps, which is less than half that required for SP1 or the prototype.

Also, as seen in Figure 20, the slope reaches a nearly constant value about 3 secs after the maximum temperature, compared with more than 6 seconds for SP1.

It was concluded that the operating and response characteristics of SP2 were superior to both SP1 and the prototype, and that the SP2 design should be used for future development.

7.4 Correlation of SP1 and SP2 results

Although SP1 turned out to be an inferior probe to SP2, nevertheless it is a usable instrument, and provides useful data. Since SP1 and SP2 are different and are of different size and design, it is instructive to see if their results can be correlated.

Fig. 17. Comparison of Model with Data, SP2 Probe, $V=2.5$ m/s

Fig. 18. Comparison of Model with Data, SP2 Probe, $V=8.6$ m/s

Fig. 19. Comparison of Model with Data, SP2 Probe, $V=16 \text{ m/s}$

Fig. 20. Slope vs. Time for SP2

The table below summarizes the results from the two probes:

SP-1

<u>V m/s</u>	<u>q w/cm³</u>	<u>h w/cm²-k</u>	<u>S</u>
2.42	1689	.0083	-.0921
8.60	1721	.0191	-.1713
15.97	1704	.0273	-.2314

SP-2

2.49	8501	.0161	-.2072
8.60	8234	.0289	-.3562
16.0	8454	.0385	-.4686

Figure 21 shows that, when slope S is plotted against h there is no correlation between the two probes. However, according to the simple theory of operation of the TTA,

$$S = \frac{4h}{\rho C_p d} \quad (5)$$

where d is the diameter of the probe. Therefore, a plot of S vs h/d should be linear and should fall on the same line for any diameter. Figure 22 indicates that this is indeed the case, at least for those two probes.

Finally, the heat transfer from each probe was calculated in terms of log Nu vs log Re, and compared with data reported by McAdams for heat transfer from cylinders. The agreement shown in Figure 23, is good, especially for SP2.

8.0 EFFECT OF AXIAL HEAT CONDUCTION

The theory of TTA operation, outlined in Section 2, assumes only radial heat transfer. However, heat transfer in the axial direction is also possible, and could have a significant effect on the response of the instrument. It is reasonable to expect that any axial heat transfer effect would be more pronounced in a locally-heated probe, such as SP1 and SP2, than in the prototype where the entire length of thermocouple wire was heated.

Slope vs Heat Transfer Coefficient SP1 and SP2 probes

Fig. 21. Slope vs. Convective heat transfer coefficient for SP1 and SP2 Probes

Slope vs Heat Transfer Coeff.
SP-1 and SP-2

Fig. 22. Slope vs. h/d for SP1 and SP2

Log Nu vs Log Re for SP1 and SP2 Compared with McAdams data

Fig. 23. Log Nu vs. Log Re for SP1 and SP2

The effect was investigated using the SINDA model of SP2. Previous sections have shown that the model is an accurate portrayal of the instrument response. Axial heat transfer was promoted by assuming that part of the probe was insulated along its length, thus restricting radial heat transfer. The extent of axial insulation was varied so that a comparative investigation of its effect could be made.

The SP2 probe is heated for a distance of about 1.25 cm from the end cap. SINDA runs were made assuming that the insulation starts at 0.4 cm, 0.7 cm, and 1.0 cm from the end cap. Figure 24 shows that as the uninsulated length decreases, or as the length of probe that is insulated is increased, the slope changes quite dramatically. The fastest response, i.e., the time for the value of the slope to become constant, is predicted to occur when the uninsulated length of probe is 1 cm. If the uninsulated length is shorter, or if there is no insulation at all, the time it takes to reach constant slope is increased. It is important to note that the response of the instrument starts to change as the insulation starts to overlap the heated section of the probe. The transition between the insulated and uninsulated section is roughly equivalent, in terms of heat transfer rates, to the boundary between the part of the probe in the airflow and the part out of the airflow. These results then indicate that for a consistent and rapid instrument response, care should be taken to ensure that the heated part of the sensor is completely within the flow being measured. Also, putting an insulated sleeve over the non-heated part of the probe would improve the response.

9.0 CONCLUSIONS

1. A computer model of the TTA was developed. Results of the model were in good agreement with experimental data from the prototype instrument, and consistent with data in the literature for heat transfer from heated cylinders. The model can, therefore, be used with confidence for a wide range of TTA probe designs and operating conditions.
2. The model was used to analyze the response of two locally heated probes. Agreement between model and experimental data was good. It was found that one of the probes (designated SP2) had superior characteristics with respect to power requirements and time of response.
3. It was found that the slope (i.e., the rate of temperature decay) could be correlated for both, different size, probes when plotted against the ratio of heat transfer coefficient to diameter.
4. Using the model, it was determined that axial heat conduction plays a significant role in the response of the locally heated probes. It is important that the heated part of the probe be completely in the flow stream being measured, and that the non-heated part of the probe be insulated.

Fig. 24. Slope vs. Time for various insulated lengths of probes

10.0 REFERENCES

1. J. L. Bailey et al, "Evaluation of the Performance Characteristics of a Thermal Transient Anemometer," Journal of Experiments in Fluids, Vol. 15, 1993.
2. F. Kreith, "Principles of Heat Transfer," 4th Edition, 1986.
3. T. H. Bauer, "A General Analytical Approach toward the Thermal Conductivity of Porous Media," International Journal of Heat and Mass Transfer, Vol. 36, No. 17, 1993.
4. T. H. Bauer, private communication.
5. W. H. McAdams, "Heat Transmission," 3rd Edition, 1954.