COMBINED PROBE FOR MACH NUMBER, TEMPERATURE AND INCIDENCE INDICATION

Jiri Nozicka*, Josef Adamec*, Daniel Hanus**
***Department of Fluid Dynamics and Power Engineering, **Department of Automotive and Aerospace Engineering**
Faculty of Mechanical Engineering, Czech Technical University in Prague, Technicka 4, 166 07 Prague 6, Czech Republic

Keywords: *flow speed, temperature, incidence, measurement, thermocouple*

Abstract

New application possibilities of the thermometers for the purpose of the measurements of the mean velocity flow field, which is the vector of velocity and its direction in the space is described. The application is based on the directional characteristic (recovery factor) of the cylindrical shaped termocouple probe and its specific course. The influence of the angle of attack of the gas flow on the measured temperature allows with a very good accuracy to use a thermocouple probe as an element of the velocimeter probe like a pneumatic probe. So that specially adjusted thermocouples with the configuration of 3 or 5 elements form the probe that can indicate the velocity of the gas flow and its direction in the plane or space eventually. The accuracy of the measurements increases with Mach numbers.

The simplicity, easy operation and maintenance of those probes destine them for use in an airborne application as well as in experimental research. Some simplified modifications of such a probe are suitable as flow direction indicators – as an angle of attack or stall indicator in aircraft aerodynamics or as a surge indicator in turbo machinery.

1 Introduction

This paper presents some new applications for a method of flow speed measurement with help of at least two different thermometers. The principals of this method are described in the simplest way in [1]. Further development of the method mentioned led to the design of the probe for indication of angle of attack - in fact an analogical probe to a three or five hole pneumatic one.

2 Basic Theoretical Overview

For the purpose of the paper presented let's adopt the following description of probe behaviour:

- Temperature probe is described by a dimensionless error of the temperature measured, often called over all recovery factor r, see [2],

$$r = \frac{T_i - T}{\frac{c^2}{2c_p}} = 1 - \frac{T_0 - T_i}{\frac{c^2}{2c_p}} \qquad (1)$$

where T, T_0 and c are free stream temperature, total temperature and velocity, c_p a specific heat capacity at constant pressure and T_i a temperature indicated by a probe. The prediction of the numerical value of r is usually difficult, and thus an experimental way - the probe calibration - seems to be unavoidable. For this purpose the application of the theory of similarity gives the most representative results, r is then given as a function of Reynolds and Mach numbers Re and Ma, Strouhal Sh and Fourier Fo numbers, Poisson number κ, angle of attack - pitch α and yaw β, and some others describing the influence of heat radiation and conduction, and, of course, of a probe geometry.

- Five-hole probe properties should be described in a dimensionless way, as well. The following parameters are very useful:

  Total pressure parameter

  $$\Pi_0 = \frac{p_0 - p_2}{p_2 - p_{ss}}, \qquad (2)$$

  Dynamic pressure parameter

  $$\Pi_\mathrm{d} = \frac{p_0 - p}{p_2 - p_{ss}}, \qquad (3)$$

  Pitch angle parameter

  $$\Pi_\alpha = \frac{p_1 - p_3}{p_2 - p_{ss}}, \qquad (4)$$

  Yaw angle parameter

  $$\Pi_\beta = \frac{p_4 - p_5}{p_2 - p_{ss}}, \qquad (5)$$

Here p_i means the pressure indicated by hole i. p_o and p are total and line pressure of the stream and p_{ss} is a mean indicated line pressure,

$$p_\mathrm{ss} = 0.25\ .\ (p_1 + p_3 + p_4 + p_\mathrm{s}\ ) \qquad (6)$$

All parameters Π_i are then to be considered as functions of Mach and Reynolds numbers and pitch and yaw angles, respectively.

3 Sheeted Thermocouple Probe

In the introduction in this paper a method of evaluation of a free stream velocity with help of the data of two different thermometers was mentioned. In [1] it has been proved, that a pair of sheeted thermocouples with different angles of attack can create the simplest combined total temperature and flow speed probe. The following formulas for flow speed and total temperature, valid for the probe containing two perpendicularly fixed K type thermocouples, were derived and experimentally verified:

$$c = 21.97(\Delta U)^{1/2}\ ,\ \Delta U = U_1 - U_2 \qquad (7)$$

$$T_\mathrm{t} = 20.1(U_1 + U_2) + 1.353.10^{-4}.\ c^2$$
$$= 20.1(U_1 + U_2) + 0.0653.\Delta U \qquad (8)$$

Here $U_{1,2}$ are thermoelectric voltages measured by a data acquisition system. The results obtained were based on the results of a single sheeted thermocouple, measured by the author on a great set of sheeted K - type thermocouples by various manufacturers and dimensions, see fig. 1. It is valid with good accuracy for $0.2 < \mathrm{Ma} < 0.8$ and $5.10^3 \le \mathrm{Re} \le 5.10^4$.

4 More complicated probes

Let's now study the function $r = r\,(\alpha)$ in fig. 1 in more detail. There are two local peaks at about zero and 90 deg. incidence. Both extremes are flat. However, between 0 and cca 75 deg the function has a simple form and can be mathematically expressed as

$$r = 0.786 - 0.0000305\ .\ \alpha^2,$$
$$\alpha \text{ in angular degrees .} \qquad (9)$$

If the incidence of a thermocouple will be large enough, let's say 60 deg, its signal will vary with a small change of α . Using this effect, we can create more-thermocouple probes similar to three or five-hole pneumatic probes, being able to indicate the direction of the flow stream as well.

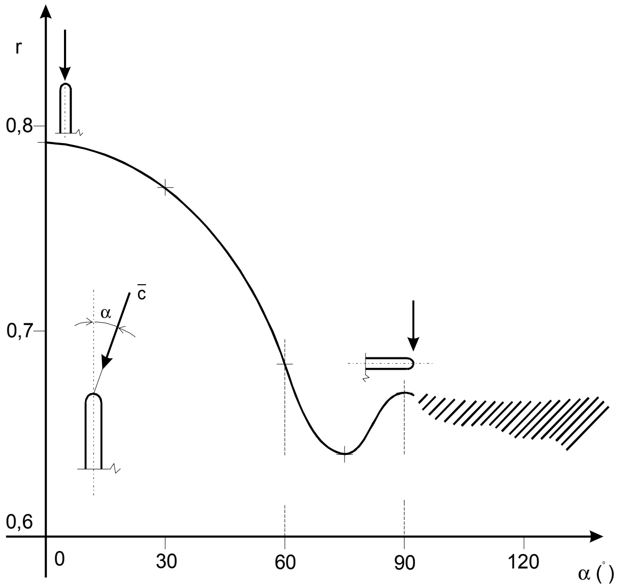

Fig. 1

5 Three-thermocouple Probe

Three sheeted thermocouples with their relative angle ε = 60 deg. create the simplest combined probe for total temperature, flow speed and pitch angle measurement (see fig. 2). Thermocouples TC1 and TC3 indicate the same temperature $T_1 = T_3$, if the probe has just a zero incidence. This position can be found rotating the probe around its shaft. The numerical value of α can then be read directly from the scale on a support. The flow speed can be calculated in a similar way as in the case of the two thermocouple probe. If there is no possibility to rotate the probe, some more complicated method similar to one developed for a pneumatic probe is to be used. The behaviour of this probe from the point of view of the velocity measurement can be described by parameters Z, defined analogicaly to the Π - parameters, see eq. (2) to (6). Ignoring the total temperature measurement, the following two Z - parameters exist:

$$Z_c = \frac{T_2 - T_s}{c^2} \text{ flow speed parameter,} \qquad (10)$$

$$Z_a = \frac{T_3 - T_1}{T_2 - T_s} \text{ pitch parameter,} \qquad (11)$$

here T_i are temperatures indicated by TC1 to TC3 and $T_s = 0.5 \,.\, (T_1 + T_3)$.

To predict the numerical values of parameters Z, see (10) and (11), we can use the simplified thermocouple angular characteristics (9). If the probe is positioned in the flow stream with an incidence of α deg., the angles of attack of the three thermocouples are:

$$\begin{array}{ll} \text{TC 1} & \alpha + \varepsilon, \\ \text{TC 2} & \alpha, \\ \text{TC 3} & \alpha - \varepsilon, \end{array} \qquad (12)$$

Recovery factors are then:

$$r_1 = r(\alpha + \varepsilon) = \\ = 1 - \frac{T_0 - T_1}{\frac{c^2}{2c_p}} = 0.786 - 0.0000305.(\alpha + \varepsilon)^2,$$

$$r_2 = r(\alpha) = \\ = 1 - \frac{T_0 - T_2}{\frac{c^2}{2c_p}} = 0.786 - 0.0000305 \cdot \alpha^2, \qquad (13)$$

$$r_3 = r(\alpha - \varepsilon) = \\ = 1 - \frac{T_0 - T_3}{\frac{c^2}{2c_p}} = 0.786 - 0.0000305.(\alpha - \varepsilon)^2,$$

From (13) the following expressions can be easily derived:

$$Z_c = 0.0000305\,\varepsilon^2, \qquad (14)$$

$$Z_a = \frac{4 \cdot \alpha}{\varepsilon}.$$

If we now assume that $\varepsilon = 60$ deg, we can rewrite (14) as:

$$Z_c = 0.11 \qquad (15)$$

$$Z_a = 0.0\overline{66} \cdot \alpha \qquad (16)$$

Both (15) and (16) seem to be very simple, but it is still necessary to have in mind, this is due to the simplification of sheeted thermocouple behavior, using (9). The qualities of a real probe will be in good accordance with (15) and (16) for small $\alpha \leq \pm\ 20$ deg only.

To confirm (15) and (16), the probe described was calibrated. The results of such measurements in comparison with diagrams of (15) and (16) are in fig. 3.

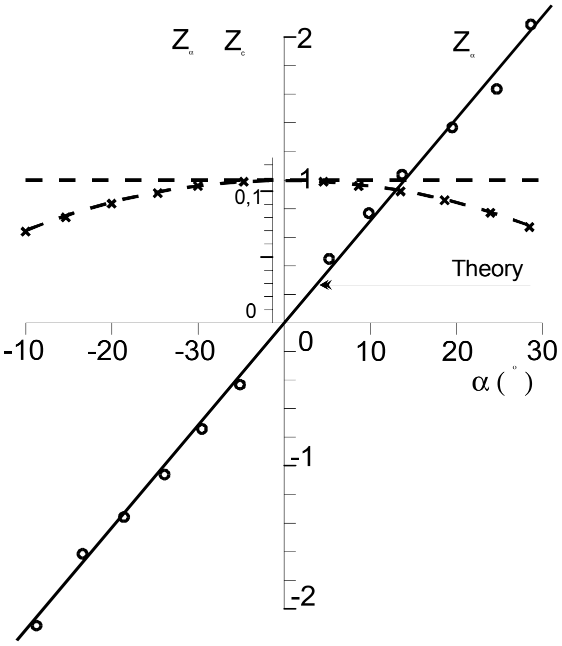

Fig. 3

6 Five-thermocouple Probe

The addition of two more thermocouples as shown in fig. 4 allows us to measure the yaw angle β as well. One more Z - parameter is now

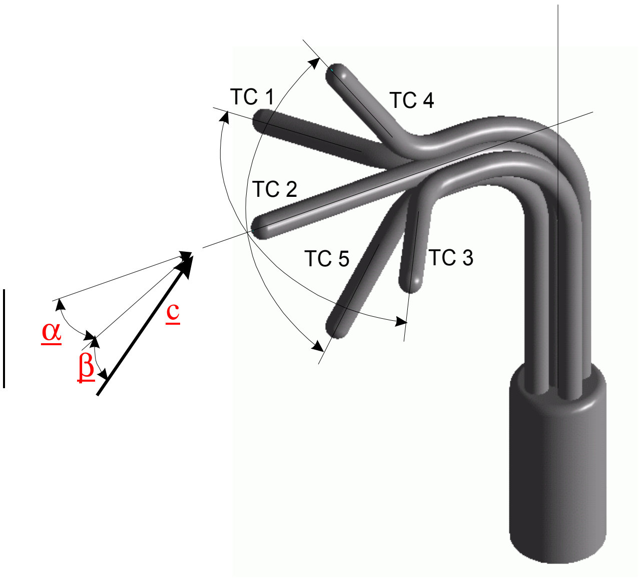

Fig. 4

defined using the signals of these two additional thermocouples:

$$Z_\beta = \frac{T_4 - T_5}{T_2 - T_s} \quad \text{yaw parameter.} \qquad (17)$$

In case of a five-thermocouple probe, the mean temperature Ts should be defined as

$$T_s = 0.25.(T_1 + T_3 + T_4 + T_5)$$

Similar to pneumatic five-hole probes, several types of operation are possible as well. One is the simplest way, from the point of view of the data evaluation - the free movable probe. That means it is possible to change both pitch and yaw angles of the probe, which can then be balanced just into the direction of the flow. We simply have to find that position, where $T_1 = T_3$ and $T_4 = T_5$. The value of α and β can be read on the scale of the supporting device immediately.

The simple way of measurement and wiring is unfortunately violated by the very complicated construction of the support.

Another possibility is to mount the probe, as it is semi-adjustable. Usually it is quite easy to turn the probe around its shaft. In this case the position where $T_1 = T_3$ can be set. Then, using signals of thermocouples TC2, 4 and 5 only, yaw angle β can be find, when using the probe as the fixed three thermocouple one (see previous section).

Sometimes there is no possibility to change the probe position at all. We have to operate the probe as a fixed one. Let's assume the probe is placed into a stream with any pitch and yaw angles α and β. For the sake of simplification we can define a common spatial angle of attack χ, defined

$$\chi = \sqrt{\alpha^2 + \beta^2} \qquad (18)$$

The angles of attack of thermocouples are now:

$$\begin{aligned}
&\text{TC1} && \chi_1 = \sqrt{(\alpha + \beta)^2 + \beta^2}\,, \\
&\text{TC2} && \chi_2 = \sqrt{\alpha^2 + \beta^2}\,, \\
&\text{TC3} && \chi_3 = \sqrt{(\alpha - \varepsilon)^2 + \beta^2}\,, \qquad (19) \\
&\text{TC4} && \chi_4 = \sqrt{\alpha^2 + (\beta + \varepsilon)^2}\,, \\
&\text{TC5} && \chi_5 = \sqrt{\alpha^2 + (\beta - \varepsilon)^2}\,,
\end{aligned}$$

Obviously (18) and (19) are valid for small α and β. The recovery factors are:

$$\begin{aligned}
r_1 &= 0.786 - 0.0000305\left((\alpha + \varepsilon)^2 + \beta^2\right), \\
r_2 &= 0.786 - 0.0000305\left(\alpha^2 + \beta^2\right), \\
r_3 &= 0.786 - 0.0000305\left((\alpha - \varepsilon)^2 + \beta^2\right), \qquad (20) \\
r_4 &= 0.786 - 0.0000305\left(\alpha^2 + \left(\beta^2 + \varepsilon^2\right)\right), \\
r_5 &= 0.786 - 0.0000305\left(\alpha^2 + \left(\beta^2 - \varepsilon^2\right)\right).
\end{aligned}$$

In the same way as in the previous section we can now obtain

$$Z_c = 0.0000305 \cdot \varepsilon^2\,, \qquad (21)$$

$$Z_\alpha = 4 \cdot \frac{\alpha}{\varepsilon}\,, \qquad (22)$$

$$Z_\beta = 4.\frac{\beta}{\varepsilon}\,, \qquad (23)$$

and further for $\varepsilon = 60$ deg

$$Z_c = 0.11\,, \qquad (24)$$

$$Z_\alpha = 0.0\overline{66} \cdot \alpha\,, \qquad (25)$$

$$Z_\beta = 0.0\overline{66} \cdot \beta\,. \qquad (26)$$

These results are based on simplifications similar to those described by (16) and (17), so the probe calibration is unavoidable as well. There is the probe velocity parameter Z shown

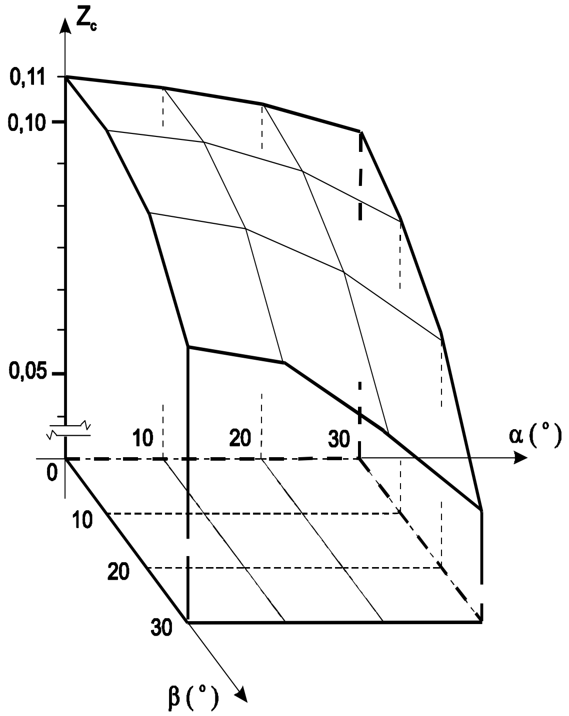

Fig. 5

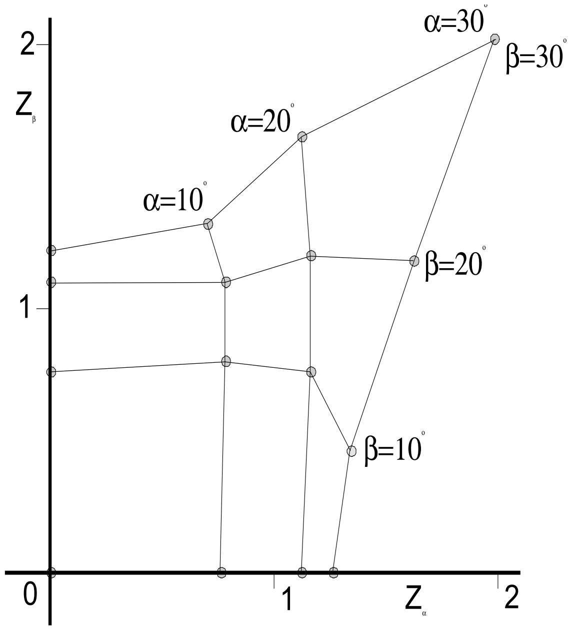

Fig. 6

as a function of pitch and yaw angles α and β in fig. 5. It is obvious there is a good accordance with theoretical values for small $\alpha,\beta \le \pm 15$ deg. only. For greater incidence the value of Z_c is dropping.

The angular characteristic of a five thermocouple probe can be introduced in the form of the diagram Z_α, $Z_\beta = f(\alpha,\beta)$, developed for five hole pneumatic probes. There is an example of one in fig. 6. A good accordance between theory and experimental data for small α and β is obvious again.

7 Some Special Applications

In previous sections it is described how to use several thermocouples for the measurement of velocity and direction. This allows us to design the flow speed probes independent of pressure measurement, which can help us check the results of measurement. Moreover, as shown in [1], for higher Mach numbers, $Ma > 0.5$, the accuracy of such probes can be better than that of the pneumatic sensors.

From the other point of view, it is possible to design some simplified sensors, based on results described above, corresponding to special kinds of measurement. For the use in turbomachinery the following two special applications have been designed.

8 Probe for Measurement of Surge

A part of experiments on compressors - and sometimes the most dangerous one - is the measurement of the unstable part of the characteristics of a compressor, especially during so called surge. The most complicated problem from the point of view of the data acquisition system is the sudden change of the flow direction. Probes designed in a conventional way cannot provide sufficient signals during this period. From the other point

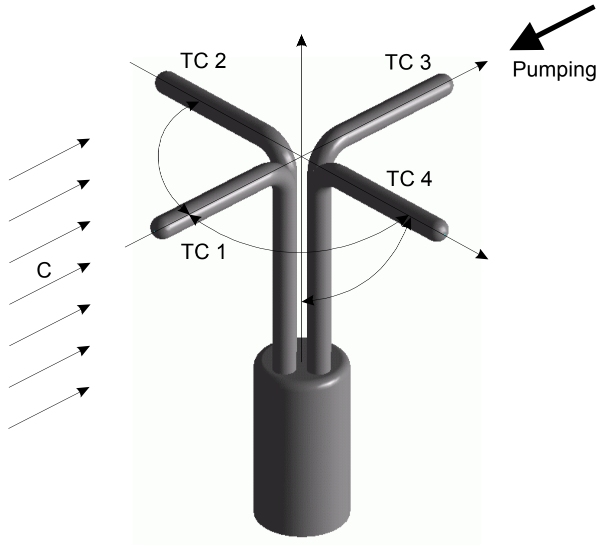

Fig. 7

of view, special probes for indication of phenomenon mentioned often have much worse parameters in a stable regime. There is a simple solution to this problem shown in fig. 7.

Thermocouples TC1 and TC2 create a two thermocouple probe and serve as a common flow speed measurement. TC3 is in this situation in the weak past this probe, its signal is similar to that one provided by TC2. During the surge cycles the flow reverses, TC 3 indicates now the highest temperature.

9. Airborne Applications

Obviously probes shown on fig. 2 and 4 were designed as an option to pneumatic three or five – hole probes. They are thus suitable for the aerodynamic research of flow fields during experiments in wind tunnels of similar facilities. Moreover, after simple changes in respective position of the thermocouple used special probes useful for application in aircraft control systems can be derived.

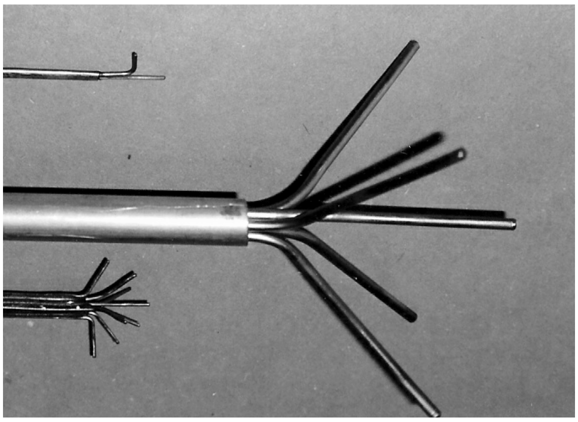

Fig. 8

The simplest configuration of a probe designated for aircraft speed, angle of attack and yaw angle indication is shown on the fig. 8. The probe is practically identical with that shown on the fig. 4; entirely the thermocouples are fixed parallel to the shaft axis. The shaft ensures the thermocouples are placed far in the unaffected flow, i.e. in front of the leading edge of the wing or nose of the fuselage. In this case, the stiffness and reliability of the probe would be preferred to a minimization of their dimensions, so that thermocouples of 3 mm diameter would be preferred.

If higher range of angles indicated should be ensured, some additional thermocouple could be installed, as shown on the fig. 9. For further data evaluation only three

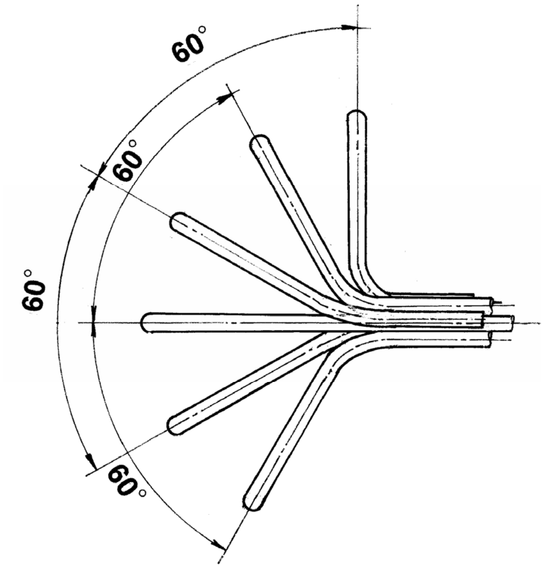

Fig. 9

of them would be preferred. As a basic one that with the highest indicated temperature should be chosen, supplied with two other having relative position to this one of ± 60 deg.

For the installation in the aircraft fuselage the integration of more temperature sensors into one combined probe need not to be acceptable solution. Even in such case the idea described could be applied. The individual thermometers could be, for example, built into the surface of the nose of the fuselage, as shown on the fig. 10. The indicated temperature of any of them is than affected by the velocity distribution on the fuselage. The data evaluation proceeds in a similar manner as described, the numerical values of coefficients in (21) to (23) should be determined experimentally by the calibration. Obviously, the shape of the fuselage nose and the position of individual thermometers will be determining in this case.

10 Accuracy of the method

The error of the measured velocity of the flow depends on the parameters of the flow, that is velocity, or Mach Number respectively and on the other side on the used measurement

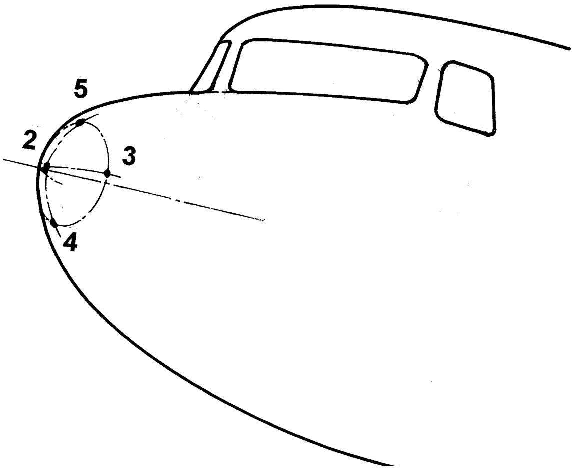

Fig. 10

instrumentation. At the prototype of the velocimeter probe we have used thermocouples Haereus, which have been calibrated on the very accurate calibrating device in the measurement department of the CKD Praha Company. For the measurements of the flow parameters using new probe very accurate instrumentation has been used, like measuring central with range of 0.1 Volt and accuracy 0.01% and seven-digit voltmeter, so that the measured tension of the thermometers were indicated in microvolts. The accuracy of the measurements of the velocity at the velocity about 100 meters per second is comparable to Prandtl (or Pitot – static) pneumatic probe, that is 2%, while using simple two-thermocouple probe. At lower velocity the accuracy decreases, but at higher velocities, for instance at 150 meters per second the error is only 1% and over 200meters per second under 0.5%. The use of the probe at Mach Numbers around 1 is without problem. The accuracy of the measurement of the angle of attack of the flow is about ±0.5° at angle of attack in the range ±15°. At higher angles the error increases to about ±1.0°. The probes with 3 or 5 thermocouples measure the velocity and the angle of attack with similar accuracy at smaller angles of attack. At greater angles of attack the sensitivity of the probes decreases and therefore the errors grow. At angle of attack 30° is error approximately double of simple two-thermocouple probe. In general it is possible to say that new probes are much better in comparison with the pneumatic ones at very high subsonic velocities of the fluid flow and at Mach Numbers around 1 cause considerably smaller problems.

References

[1] Nožička, J. Unconventional Probe for Flow Speed and Temperature Measurement *Proc FLUCOME'94*, ONERA CERT, Toulouse, France, pp. 11-17, 1994.

[2] Nožička, J.: Calibration of a Temperature Probe with respect to the Influence of Heat Conduction and Radiation, *Proc 9th International Conference on Thermal Engineering and Thermogrammetry*. Budapest, Hungary 1995.

Acknowledgements

This research was supported by the Czech Ministry of education, Sports and Youth, by grant No J04/98:212200009.