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Measuring Techniques and Analogue Techniques 2
(Anemometry, Thermometry, Radiometry)

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Introduction: The seven papers of this session include a variety of topics in measuring techniques with application to heat transfer. First we shall consider two theoretical analysis for the use of hot-film anemometers to determine local flow characteristics and local heat transfer. Two other papers offer new techniques to determine surface temperatures and local heat transfer coefficients on relatively large areas: the phosphor coating, and the liquid-crystal technique. The fifth paper describes an improved hot-wire method for turbulence measurements in non isothermal air flows. The following paper is concerned with an analytical study of design parameters affecting the accuracy of thermocouple measurements especially in the heatshield of a reentry vehicle. The final paper presents an investigation on nocturnal radiation measured by a new developed differential radiometer.

Paper Review:

MA 2.1
Theoretical Analysis of the Use of Miniature Film Probes for the Determination of the Local Characteristics of the Boundary Layer.

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In this paper a theory is developed for hot-film anemometers, diffusion electrochemical probes, microelectronics circuits, etc. with extremely small dimensions of the instruments. Those small proportions of only a few microns in the direction of flow are necessary for local measurements of friction, heat and mass transfer, fluctuations of the viscous sublayer of turbulent boundary layers ect.. The miniature thermal or diffusion film probes mounted at surfaces beneath the fluid are practically identical in operation principles, therefore the solutions determined in this paper are valid for all cases of heat and mass transfer if the analoques relations are taken into consideration.

For this problem the total conservation equation can be written in dimensionless form (equ. 3 of MA2.1) using the transformation of fig. 1:

$$\frac{\partial^2\Theta}{\partial X^2} + \frac{\partial^2\Theta}{\partial Y^2} - LY\frac{\partial\Theta}{\partial X} = 0 \qquad (1)$$

with the boundary conditions (equ. 4 MA 2.1):

$$\Theta(X,\infty) = 0; \quad \left(\frac{\partial\Theta}{\partial Y}\right)_w = \begin{cases} 0 \text{ when } X<0 \text{ or } X>1 \\ K_o(1-\Theta_w) \text{ when } 0<X<1 \end{cases} \qquad (2)$$

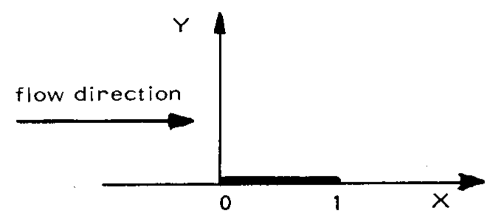

Fig. 1

Equ. (1) and the conditions (2) contain two parameter, the dimensionless width L of the probe determined from the friction velocity and the relative reaction rate K_o.

Equ. (1) can be solved generally if the longitudinal molecular diffusion is neglected: $\partial^2\Theta/\partial X^2 = 0$, which considerably simplifies the boundary conditions, (equ. 5 MA2.1):

$$\Theta(0,Y) = 0; \quad \Theta(X>0,\infty) = 0; \quad \Theta(0<X<1,0) = 1 \qquad (3).$$

Under these conditions Leveque [1] already 1928 solved equ. (1). But this solution can be applied only for sufficiently wide probes and for sufficiently rapid reactions only. Near the leading and trailing edges of the probe the term $\partial^2\Theta/\partial X^2$ cannot be neglected and the real rate of the chemical reaction or the heat transfer is finite.

A numerical analysis of the problem based on equ. (1) under the simplified boundary conditions (3) is given by Ling [2], but this solution is not comprehensive for the reasons stated above and the estimates of the influence of finite rate of reaction under the boundary layer approximation is in contradiction to $\partial^2\Theta/\partial X^2 = 0$.

The authors of this paper used the numerical method from Ling by successive iteration. But the main difference of the solution presented here is that the varying boundary conditions are considered. The analysis was carried out in the practicable range of $25 \leq L \leq 500$ and $0.1 \leq K \leq \infty$.

The results are represented in six figures: Fig. 1 of MA2.1 shows the curves of constant concentration in the vicinity of a diffusion of a uniform length, but with different reaction rates. The effect of longitudinal molecular diffusion causes concentration changes before the probe edge, but this effect decreases with decreasing reaction rate K.

Fig. 2 of MA2.1 shows that with increasing length L of the film probe and reaction rate K the role of edge effects decrease.

In fig. 3 and 4 the concentration gradient along the probe length and at the leading and trailing edges are represented.

With the numerical results analytical expressions are obtained, which well approximate the results of exact calculations. These formulas could be a help for practical application.

The result of this paper can be useful in the study of turbulent flows, they can form the initial data for the derivation of the transfer function interconnecting the fluctuations of the current of the probe with the fluctuations of the flow.

MA 2.3
Analysis and Interpretation of the Response of Coated Thin-Film Heat Flux Gages.

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The authors investigate the influence to the response of coated thin-film heat flux gages. It is known that thin-film heat flux gages are used to measure time-dependent heat transfer rates in short-duration transient flows such as those generated in shock tubes and shock tunnels. The film is usually platinum with a thickness of approximately 0.1 µm and is deposited on a ceramic substrate that is of sufficient thickness to behave as a semi-infinite medium during the time period over which the heat flux is to be measured. The platinum film serves as a resistance thermometer with very rapid time response of only few microseconds. In most cases the presence of the film is negligible, and the temperature can be taken as that which would exist on the substrate surface without the presence of a film. This is typically a one-dimensional, semi-infinite heat conduction problem, for which the differential equation is solved, and for this special case Camac and Feinburg [3] give the time-dependent surface heat flux q(t), equ. (1) in MA 2.3. For certain applications it is necessary to apply a protective coating over the film to shield the film from phenomena in the flow which may demage the film or influence the gage signal, for instance, if ionization in the flow occurs. To overcome this difficulty quartz coatings ranging in thickness from 0.1 to 0.6 µm have been successfully used. However, the presence of the coating impairs the gage time response. It is now the purpose of this paper, first, to investigate the influence of coating and film thickness on gage response and second, to develop a method for interpreting the signal of the coated gage to determine the time-dependent heat flux incident on the gage surface.

The time response of the coated gage is analysed by the authors by solving the direct heat conduction problem to determine the time-dependent temperature distribution in a composite semi-infinite solid consisting of the coating, the film, and the substrate, fig. 2 (see fig. 1 in MA 2.3).

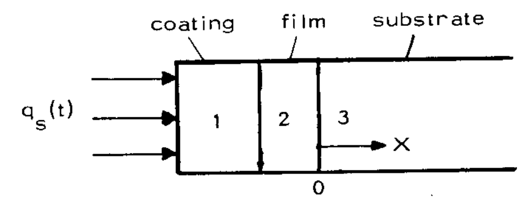

Fig. 2: Composite Semi-Infinite Solid

Assuming that heat conduction is one-dimensional and between the three materials is perfect thermal conduct, and that the materials are isotropic and homogeneous, the problem is to solve simultaneously a system of three differential equations, with the boundary conditions that the temperatures on the connecting surfaces are equal. The authors solved this systems of equations by application of Laplace transforms for two forms of heat flux: $q_s(t) = Q$ and $q_s(t) = Q/\sqrt{t}$ similar to those encountered in shock tubes flows. In this paper especially the most interesting results for the platinum - film are presented, where as detailed results for the surface temperature and the temperature distribution in the solid are reported by the same authors in [4].

The results are illustrated in some figures and discussed with the help of them. As expected, the gage response depends on the thickness of the platinum film as on the coating thickness. But also it can be seen that the heat flux variation with time does have an significant influence on gage response. Thus the success of this method for determining heat flux hinges on prior knowledge of the form of the heat flux. An assessment of this influence had been made by considering a given gage response varying only the form of heat flux used before and comparing the computed heat flux values with the heat flux that produced the given gage response. It is shown that it is necessary to make an assumption for the form of the heat flux variation with time, but this form must not be precise to obtain reasonable accurate results.

The error is more significant when the presence of the coating-film combination is ignored. In practice, it is difficult to measure the small thickness of the platinum film and the coating with such accuracy that the errors introduced into the computed heat flux remain small enough.

MA 2.4

A Non Contact Methof of Measuring Surface Temperature.

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It is an old problem and till now only unsufficient solved to measure accurate surface temperatures. The difficulties of this problem increase with enlarging the measured surface. The authors of this paper describe a technique for measuring two dimensional distribution of temperature over a relatively large surface in a laboratory experiment. The technique uses a phosphor coating on the surface which is illuminated locally with ultra-violet light. This technique is briefly described by several authors but in this paper it appears first time as a measuring technique in convective heat transfer investigation.

The phosphor technique described in this paper was used for investigation concerned with turbulent flow over a flat heated surface and to study the effects on local heat transfer on the flat surface of bluff bodies and vortex generators attached to it. The area of temperature measurement was about 1.25 by 0.6 m in a rectangular cross-section of a wind tunnel. For this large area a very large number of thermocouples or resistance devices would have been required to cover properly the surface. Other temperature measurements techniques like temperature sensitive paints and wax coatings give not the desired accuracy of measurement. Infra-red thermometers were found to be too expensive for the desired accuracy. The phosphor technique offers the possibility of recording the temperature distribution over the surface pictorially at a reasonable cost and with an accuracy approaching 1 K.

For particular applications different phosphors are available with different traces of silver and cobalt, which have in different temperature ranges up to 400 °C an approximately linear light output versus temperature, see fig. 1 MA 2.4. But the characteristic curve for light output is also affected by the intensity of the ultra-violet radiation. This fact means that a constant intensity of ultra-violet illumination must be used, and that for accurate results a calibration test should be carried out in the apparatus in which it is to be used, and at each time the surface is recoated with phosphor. Sure a disadvantage of this method is, that all observations must be made under dark room conditions.

The original intention of this method was to photograph the phosphor coated area of the heated wall during a test and from the negative to assess the variation in the light output and hence the locally surface temperatures. But it is not easy to develop the ultra-violet illumination over a large area with constant intensity. Therefore the authors used a spot reading technique, at which the ultra-violet source and the measuring head of a photometer were combined into one unit and mounted on a carriage with wheels, see fig. 3, MA 2.4. The carriage could be traversed transversely and axially at a constant height above the working section of the wind tunnel. In the paper the experimental procedure to handle with the phosphor technique is described in detail. The temperature calibration was produced with data from four thermocouple positions.

The reproductivity of heating up and cooling down measurements fell within ± 1 K, see fig. 4, MA 2.4. The curve of intensity versus temperature can be represented by three straight lines.

The technique describes in this paper is suitable for measuring two dimensional variations of locally constant temperature over relatively large areas with an accuracy of about 1 K. For small areas a photographic registration is more convenient. The advantage of the photographic method is, that with time changing temperature fields can be registrated.

MA 2.5

Local Convective-Heat-Transfer Coefficients for Jets Impinging on a Plate; Experiments Using a Liquid-Crystal Technique.

C. den Ouden and C. J. Hoogendoorn
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In this paper a relatively new method is used to determine local convective-heat-transfer coefficients. Local surface temperatures are measured using a liquid-crystal technique.

Certain organic compounds pass through an intermediate phase during the thermal transformation from the solid to the liquid state. In this intermediate phase or mesophase the molecules are movable but still ordered, this means, that the mesophase is mechanically a liquid and optically a crystalline and therefore called liquid crystals. A cholesteric liquid crystal system responds to changes in temperature by sequentially passing through the complete visual spectrum in a few degree centigrade. The change in colour is reversible, therefore this method can be used for temperature measurements. Depending on the cholesterol ester used the colour change occurs at different temperature levels. Using liquid crystals for accurate temperature measurements they must be protected against surrounding air, and mechanical influences. The protection can be done by making a solution of polyacrylate resin and liquid crystals in a special solvent.

This solution is sprayed on the surface and after the solvent has evaporated a suspension of liquid crystals in polyacrylate resin will remain, see fig. 1, MA 2.5. In this suspension the liquid crystals reflect light in all directions. The colour-temperature relationship can be found by placing a reference plate sprayed with the same liquid crystals in a thermostat. The authors insure that with this system temperature differences up to 0.1 K can be measured.

In this paper the liquid crystal technique is used to study local heat transfer coefficients from a heated surface to an impinging turbulent air jet. This problem was investigated by other authors [5, 6, 7] as a mass transfer problem using naphthalene plates to impinging jets and as a heat transfer problem using thermocouples and heat flux measurements over certain areas of the plate. The advantage of the new technique is that direct measurements of local temperature over the whole plate are possible without obstruction to the flow or heat flux in the plate.

The experimental arrangement was as follows: One side of a glass plate is kept by water at a constant temperature, the other side being cooled by the air jet. The air cooled side of the glass plate is coated with a thin layer of liquid crystals with a thickness of about 50 um. If the temperature on the water side is constant, than the heat transfer coefficient can easy determine with the measured surface temperature on the air side, see equ. (1) in MA 2.5.

The authors found very interesting results, but I hope they will understand that in this session for measuring techniques there remains no time to discuss the results in detail. The comparison with the results of other authors show that in some regions and at some Re-numbers the local Nusselt-numbers are not in good agreement.

The measuring technique using liquid crystals to determine local temperatures and heat flux without disturbing the flow is a new tool and will be developed for application to other heat transfer problems.

MA 2.2
A Simple Technique for Turbulence Measurements in Nonisothermal Air Flows.

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The hot wire technique is well established for turbulence measurements in isothermal flows. Additional difficulties set in for its use in nonisothermal flows. A hot wire anemometer operates with the rate of heat transfer from the sensor to the fluid. Therefore in flows where both velocity and temperature are varying, it is impossible to separate a single hot wire anemometer signal into its velocity and temperature components. Therefore an additional information is necessary.

Recently Chevray and Tutu [8] described a technique in which the electrical signal from a resistance thermometer is used to simultaneously and instantaneously correct the velocity signals from isothermal flow hot wire signal.

This correction process consists of two distinct operations: (a) Correction for changes in the instantaneous temperature difference between the wire and the fluid, and, (b) Correction for the instantaneous changes in the temperature depending fluid properties.
A desired automated feature of the correction requires specialized electronics and a modification of the standard instrumentation. The authors of this paper have found that the technique of Chevray and Tutu, when applied to air, can be greatly simplified with no apparent loss in accuracy. This simplification permits the use of entirely standard instrumentation, and an easy calibration procedure.

The simplification is based on the fact, that for air the decided property group is nearly insensitive to temperature variations. Hence, the anemometer output voltage must only be corrected with a multiplicative correction factor C, equ. 4b in Ma 2.2, which depends on the temperature of the wire, the reference temperature and the instantaneous temperature.

For velocity measurements in nonisothermal flows a three-wire probe has been specifically designed. The third wire was mounted in a direction normal to the plane defined by a classical X arrangement upstream for use as a resistance thermometer.

With this probe preliminary check of the entire correction were made in the smooth region of a heated jet. Fig. 2 of the paper shows excellent agreement with data evaluated from experiments compared with correction factor C from theory.

The three-wire probe was also checked in nonisothermal turbulent flows of a round free jet in a distance sufficiently far downstream from the nozzle. In this case the turbulent velocity field is self-similar and the turbulent velocity can be related to the mean velocity at the nozzle exit. With these experiments it is shown that the agreement is very good for the isothermal case and can be considered satisfactory for the heated jet. In any case, the authors reveale the usefulness of the temperature compensation technique for nonisothermal turbulent velocity measurements, though all calibrations were performed under steady flow conditions and the presented correction scheme involves the use of steady state heat transfer correlation. Some of these more or less open questions should be solved, if the measurements of the three-wire probe are compared with direct velocity measurements using a laser-doppler anemometry technique.

MA 2.6
Design Parameters Affecting the Accuracy of Isothermal Thermocouples.

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The author presents an analytical study of possible errors in temperature measurements with thermocouples. This study is specified on thermocouple assemblies, used on reentry vehicles to obtain the flight test data necessary to determine the thermodynamic performance of the heatshield and to find its contribution to the instrument's accuracy.

This paper summarizes the results of a particularity study given in the thesis of same author [9].

An isothermal thermocouple plug assembly, both in single and multiwire configurations, as used in the heatshields, was simulated with a computer program. The simulation was limited to two dimensions and did not account for all of the ablative processes involved in a reentry vehicle ablative heatshield.

The results of this study are discussed in detail but they are related to a very specified technique, so that to spare time I will only summarize the most important effects:

The thermocouple accuracy increases with decreasing wire diameter, fig. 4, decreasing lead wire length, fig. 6, increasing isothermal length, that means the length of the wire parallel to the heatshield surface, fig. 5, and increasing installation depth of the thermocouple relative to the heatshield surface.

Most of these effects are plausible if they are regarded in a qualitative sense. But a quantitative study depends on the exact knowledge of all design parameters and must be done for each new configuration.

MA 2.7
Investigation on Nucturnal Radiation Measured by a New Differential Radiometer.

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This paper is a report of an investigation on nocturnal radiation made by an improved new differential radiometer. With this radiometer a series of measurements of infrared radiation emitted by the sky and by the surface of earth were made from two sites at different altitudes during night-time hours. The measuring device includes two radiometers and a resistance thermometer which are connected to a punch tape recorder.

Each radiometer consists of two detectors, which are identically constructed but have different surface emissivities, one is painted dull dark, the other one is coated with polished electrolytic gold. With a temperature control and a power supply system the radiating surfaces of the detectors are kept at the same temperature. The difference of energies, supplied to keep the detector surfaces at same temperature, is calculated and gives directly a relation to the radiation energy.

One of the radiometer is sky-oriented, it gives the infrared radiative upward flux, while the other is ground-oriented and gives the infra-red radiative downward flux. The difference of both is the net radiation at the instrument level, see equ. (1) - (5) in MA 2.7. The net radiation does not depend on the detector temperature and can be calculated directly as the difference between the energies supplied in the two radiometers.

Radiation measurements are made under clear-sky conditions during the night time in Padova. With the observed data the atmospheric emission G can be correlated to the air temperature and water vapour partial pressure at ground level by an empirical equation, equ. 6 in MA 2.7. With the diagram in fig. 4 of the paper the atmospheric emission, the black body radiative temperature of the sky, and the net radiation from the ground can be read if the air temperature and the relative humidity at ground level are known.

Numerical values obtained from the empirical equation for the atmospheric emission are compared with values obtained from an theoretical atmospheric model by numerical integration and with the empirical correlations from Brunt's [10] and from Swinbank's [11]. The maximum deviation of the values given by the authors equation from the values of the atmospheric model does not exceed 4 per cent. The comparison between the other empirical relations are smaller than 3 per cent.

Final Remarks

As demonstrated by the papers presented here in this session, there is still considerable interest in new, and in improved measuring techniques on flows, surface temperatures, theoretical corrections and atmospheric radiation. But I am sure, that not all new or improved measuring techniques are presented only in these two sessions. We can see in these days, that for most experimental investigations new or improved measuring methods have been applied. In this sense these two sessions can only be a small representation about the measuring techniques in heat transfer.

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