# I. INTRODUCTION

This study concerns the experimental design and development for a study of air-particle flows in a turbulent boundary layer over a flat plate. Of major concern are the aerodynamics of the plate system and the test section of the wind tunnel. This is part of a NASA funded project to study effects of the flow of suspended solids of various types on drag of a flat plate. The long term objective of the project is to obtain data which will be useful in designing systems to reduce drag on subsonic airplanes. The variables to be studied in the NASA project are physical character of the particles (shape, electrical, and magnetic properties), and effects of different loading ratios in the boundary layer. Total drag and local shear stress on the test plate will be measured. A holographic techique will be used to study particle agglomeration and velocity, backed up by a high speed movie method.

Several important questions were raised concerning the basic experiment design. Instrumentation of the test plate and a requirement for bearings inside the plate suggested a thick plate design that would have to be of limited width to avoid extreme tunnel blockage effects. Would this plate support a thickened turbulent boundary layer of a self-similar nature along and across the test plate surface? A particle injection nozzle was placed upstream of the plate. Would this seriously distort the turbulent boundary layer over the test plate? Particle injection tests could be expected to leave particle residue in the wind tunnel flowfield. Could an accurate calibration of hot-wire probes be performed inside the tunnel , and could a good calibration method for boundary layer measurements be determined in that environment?

Drag reduction becomes very important as energy sources become difficult to acquire. As the cost of aviation fuel rises to record levels, the efficiency of commercial aircraft becomes more and more important[1]. In order to increase efficiency, it may be possible to apply techniques of viscous drag reduction through fluid additives. Although these techniques are not very well developed, it is known[2,3] that viscous drag can be reduced in liquids by the addition of small amounts of polymers, small amounts of various soaps, or solid particles or fibers. In gases, several investigators have observed drag reduction with suspensions of fine particles or dust. In order to determine the viability of drag reduction on aircraft with particle injection in the boundary layer, it is necessary to quantify drag reduction with particle loading, type of particle, and environmental parameters.

The phenomenon of drag reduction with additives principally occurs in turbulent boundary layers[4]. In the case of high molecular weight linear polymers such as polyethylene oxide, in liquid suspension, only a few parts per million by weight of the additive is sufficient to achieve as much as 50% drag reduction. In the case of particles in air much higher loadings have been indicated, usually mass loading ratios of order unity. Particle size is generally in the range of 1 to 1000 microns. Drag reduction in liquids is a fairly substantiated phenomena, whereas drag reduction in gases due to particle addition has been observed sporadically. It should be noted that most drag reduction has been observed in internal flows such as pipe or channel flow. In one of the few instances of tests performed on bodies in a flow of dusty gas[5], drag reduction was not observed. In fact, the drag increased with particle loading. However, the bodies were cylinders and spheres tested under very low diameter Reynolds numbers and in fairly small pipes. In this case a reduction in pressure drag would be necessary, something that has not been observed in any drag reducing flow with additives.

The Euromech 52 conference report included a short survey[4] of the state of drag reduction research. An overview of experimental work in particle additive drag reduction was also authored by Radin, Patterson, and Zakin[3,6]. That study lists eight cases in which drag reduction was observed. On the other hand, thirteen other cases are listed in which no drag reduction occurred. No correlation of drag reduction was found with any particular factor in the studies. The theory is advanced that electrostatic charges cause interaction between the particles, and the particles and the surface, producing a delayed and extended laminar to turbulent transition region. The overview does not include evidence to support that theory. Also, the theory does not explain drag reduction in liquid-particle flows, in which boundary layer measurements have been made that confirm fully turbulent flow during drag reduction[7].

Of particular note in experimental work with particulate drag reduction are the studies by Sproull[8], and by Rosetti and Pfeffer[9]. Unlike most other investigators, Sproull measured the viscosity of the gas-particle mixture with a cylindrical-type viscosi-meter especially constructed for the dusty environment. His careful study of several types of particles revealed viscosity reductions of up to forty percent. This work is generally considered reliable and is widely quoted. The study by Rosetti and Pfeffer[10] is representative of most other studies in experimental design. Their experiment concerned gas-solid flow in pipes and yielded drag reduction up to 75%. Both vertical and horizontal flows were investigated to determine the effect of gravity and settling. Their observations were that drag reduction occurred with all particle sizes (glass beads of 10 to 60 microns diameter) in the vertical tests, while only the smallest particles produced drag reduction in the horizontal test.

Although the analytical modeling of particle flow to achieve a description of the drag reduction effect is conceptually easier than modeling polymer flows, theory of particle flow is still being developed. Two papers published at about the same time (1974) indicated that modeling of particulate flows is an elusive and difficult task. Hamed and Talakoff[11] attempted a numerical, finite-difference solution of the low Reynolds number laminar case of particulate flow. Their result was that drag increased with higher particle loadings. On the other hand, Chakrabarti[12] approached the same problem and determined that the drag would decrease.

The analytical study by Saffman[13] seems to be unique in that it treats the stability of laminar gas-solid flow. He found that the addition of particles could either stabilize or destabilize the flow. Particles below a certain size would tend to trigger transition, while larger particles added to the flow would dampen laminar instabilities. Also, he found that in both cases the boundary layer velocity profile would be modified. The solution to the exact profile was not found. His results also seem to contradict the hypothesis of delayed transition proposed by Radin.

Although the general analytical studies have not produced exact determinations of boundary-layer properties or the actions of the particles, some investigators have been able to predict specific effects of the particles on different regions and structures of the boundary layer. Drew[14] reports on the production and dissipation of energy in turbulent flow with particles suspended in a fluid. Until a means can be found to take accurate measurements of flow in these particle-gas boundary layer flows, analysis provides the best means to test hypothesis against the limited observations to date.

# II. LITERATURE REVIEW

## A. LAMINAR AND TURBULENT BOUNDARY LAYERS

The origin of boundary layer theory seems to lie in the basic ideas presented in Prandtl's Heidelberg lecture[15] in 1904. He reduced the general Navier-Stokes equations for incompressible flow to the set of equations known as Prandtl's boundary layer equations. These apply to laminar flow only. The case of steady flow over a flat plate at zero incidence and zero pressure gradient was solved four years later by Blasius. He was able to reduce Prandtl's boundary layer equations to a single differential equation. A general acceptance of these boundary layer concepts was delayed for about 20 years until experimental technique advanced enough to allow examination of the boundary layer. Pioneer measurements were conducted by Burgers and van der Hegge Zijnen at Delft[16] in 1924. The general exploration of boundary layers did not really get under way until almost 1930.

The importance of transition of the boundary layer flow from laminar flow to turbulent flow was recognized in the nineteenth century. Reynolds performed fundamental experiments on boundary layer flow transition in the 1880s[17]. However, a theory of boundary layer stability that could predict transition statisfactorily did not appear until about 1930. It was at that time that Tollmein and Schlichting produced stability theories that agreed well with experiments conducted a few years later. The process of transition, however, is still being investigated. During transition the boundary layer thickness drastically increases and the velocity profile changes (see Figure 1). On a flat plate in laminar flow the skin friction is approximately proportional to the 1.5 power of velocity, while in turbulent flow it increases to about the 1.85 power of velocity. Dhawan and Narasimha[18] approached the problem of transition from the observation that turbulence is produced in an intermittant fashion in spots, which increase in frequency and finally result in a fully turbulent boundary layer. Probability theory is applied to the solution of

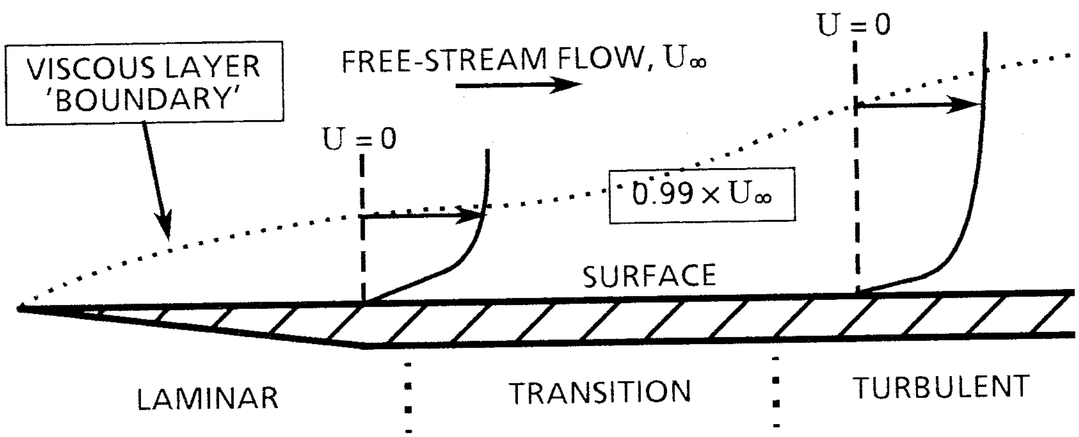


Figure 1 - Boundary layer velocity profiles and the transition from laminar to turbulent boundary layer

the boundary layer parameters during transition with some success. The velocity profiles are shown to be governed by an intermittancy factor. Lessmann[19] refined the results of Dhawan and Narasimha by applying the principle of the conditioned average.

Even though great strides have been made in analytical derivations of the properties of turbulent boundary layers, most forms of the theory are still based on the mixing-length concept of Prandtl, or on Von Karmon's similarity hypothesis[17]. An important characteristic of Von Karman's hypothesis is the use of a friction velocity ($u^*$) which is based on the shearing stress at the wall. Prandtl originated the logarithmic law of the wall from this concept, which has proved to be nearly universal in its application. The logarithmic law of the wall is, in general

$$\frac{u}{u^*} = A \log\left(\frac{y\,u^*}{v}\right) + D \qquad (22)$$

The constants ('A' and 'D') are usually determined experimentally. Schlichting[17] relates the efforts of several researchers to find the correct constants.

An important consequence of the universal law of the wall is that, if the wall shear can be found, all boundary layers can be compared to a single standard theoretical reference. Since there are two undetermined constants, the concept is not always useful. Given the large set of experimental determinations of the constants, it is possible to make some rather exact deductions. Clauser[20] used an experimental law of the wall to graphically determine the skin friction coefficient from the velocity profile without any knowledge of the wall stress. A typical example of a profile plot against the logarithmic law is shown in Figure 2. The difference between the actual profile and the law of the

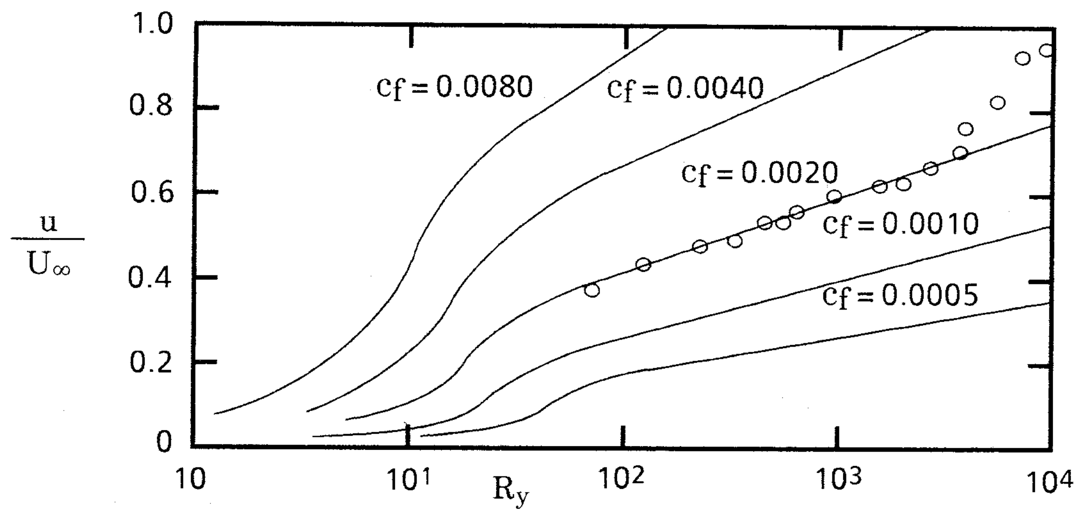


Figure 2 - Clauser's graphical solution of skin friction coefficient using the law of the wall

wall at the inner portion of the boundary layer is mainly governed by the shear at the wall. This inside portion is generally called the laminar sublayer. Even though no theoretical derivation exists which describes the complete turbulent boundary layer, it is possible to combine various approximate functions of these different parts to try to describe the entire boundary layer. Dean[21] attempted this with some success.

There are many conditions which affect the boundary layer. On a flat plate with no pressure gradient, the main influences are the surface roughness and the free stream turbulence intensity. Wu[22] has performed some of the latest experiments over rough walls, and explored the flow field near the roughness elements. Wu concurs with Clauser[20] and other investigators in the conclusion that, if the roughness height is below the laminar sublayer, then the law of the wall still holds. Simpson[23] discussed the effects of roughness elements that are higher or lower than the sub-layer thickness. Simpson makes a generalized correlation of various roughnesses, embodied in a modified law of the wall including several roughness parameters. Of particular note is the survey by Sedney[24] which discusses both two- and three-dimensional disturbances to the boundary layer.

The influence of the free-stream turbulence on the boundary layer can be quite large. Higher turbulence intensities can promote early transition of the boundary layer from laminar to turbulent flow[17]. A method for the calculation of the effect of free-stream turbulence on the turbulent boundary layer itself is given by Evans and Horlock[25]. Other phenomena that can be defined in the context of flow disturbance can produce similar transition effects. It has been observed that noise (pressure disturbance) can affect transition and the development of the turbulent boundary layer[26].

## B. BOUNDARY LAYER TESTING AND TRIPS

Early experiments concerning boundary layers established that many conditions affected the development of the boundary layer. In an early work, Dryden[16] established that the free-stream turbulence, the pressure gradient, and the leading edge shape were important factors in producing a non-disturbed flat plate boundary layer that could be compared to the theory of the times. Even the presence of dust on the plate in these experiments caused early transition of the boundary layer. In a limited way Dryden experienced the effects of roughness on transition. In a later study, Bradshaw[27] correlated the open-area ratio of turbulence damping screens in the wind tunnel to boundary layer distortion in the test section. He observed a spanwise variation of boundary layer proper-ties across a test plate with a ratio of open area to the area of the mesh below 0.57.

Experiments concerning the nature of boundary layer flow are usually performed on flat plates with little or no static pressure gradient in the flow field. This eliminates a gross disturbance of the developing boundary layer, and permits comparison of experimental results to the limited analytical theory currently available. For this reason most experiments seek to modify the normal pressure gradient along the flow direction of the wind tunnel test section to a zero gradient condition, either through the use of false walls[16], screens[28], or downstream blockages[29].

The effect of the leading edge of flat plate test articles on developing boundary layers is rarely addressed directly. A sharp leading edge gives a well-defined boundary and fixes the origin of the development of the boundary layer. However, early investigators such as Dryden[16] found that the shape of the leading edge, the flow conditions, and the alignment of the plate with the flow direction were extremely critical to avoiding disturbance of the boundary layer. Dryden found that a symmetrical leading edge was necessary, even though a small localized pressure gradient resulted at the leading edge. Although flow separation is the main concern of the design of a test plate leading edge, it was found that the shape influences transition downstream as well. More recently, Davis[30] explored the design of leading edges in detail, defining parameters for two blunt leading edge forms which can alleviate disturbance of the developing boundary layer. He computed boundary layer development on two types of leading edge geometries based on the momentum integral equation and the Pohlhausen family of velocity distributions. The Pohlhausen velocity distributions are characterized by the parameter $\lambda$. Using the criteria that separation is avoided for $\lambda > -12$, then the minimum tendancy for flow separation is obtained with a leading edge radius to thickness ratio of 1/4 and a leading edge length to thickness ratio of 4.6 (axial distance from center of nose radius to end of leading edge contour). An elliptic leading edge shape was found superior for axis length to height ratios of 5 or greater.

Two additional areas are of some interest in relation to this study and boundary layer testing. The first concerns the nature of the boundary layer over subsonic transport aircraft fuselages. The work in the area has been sparse, since the main source of drag until recent times has been the wing and other flying surfaces. Therefore the fuselage drag and its boundary layer was generally ignored or computed from approximate empirical relations. The experiments by Samuels[31] provide some answers to questions about the character of the boundary layer on subsonic jet transport aircraft fuselages. It was found that the universal law of the wall also applied to such irregular, external shapes.

Secondly, the work of Elder[32] concerning the flow past finite flat plates (finite aerodynamic width) provides one of the few instances where the influence of low aspect ratio and the flow-wise edge condition of such objects have been tested. This is not too surprising since boundary layer theory and boundary layer tests are usually concerned with flow that is two-dimensional in nature. The experiments of Elder fully characterize the edge effects on the boundary layer over the interior portions of several test plates. Elder discovered that transition occurred first near the edges and spread at an angle of 8 to 10 degrees to the flow direction from the edges inward. On plates of small thickness, a large area of two-dimensional type boundary layer flow existed over the centerline.

Many early studies were concerned with controlling transition and artificially thickening the boundary layer. Liepmann and Fila[33] investigated the effects of surface temperature and single rougheness elements on transition and discovered that the laminar boundary layer could be separated by a roughness element and still reattach as a laminar boundary layer. Under some conditions the laminar separation would result in reattachment and transition to a turbulent boundary layer. Klebanoff and Diehl[29] performed experiments on a wide variety of devices to promote thickened turbulent boundary layers, with particular emphasis on similarity in the boundary layer downstream of the devices. Klebanoff and Diehl experimented with single wires, screens, and sandpaper to thicken the boundary layer.

There has been some effort to produce some correlation between roughness of the surface and development of the boundary layer. The work of Preston[34] illustrates an analysis of the limited data of the time which is intended to predict the minimum Reynolds number for a turbulent boundary layer. Even though many such studies of boundary layer tripping and thickening have been conducted since the 1940s, basic investigations are still being performed. This is largely due to the wide variety of roughness geometries that can be used, and the fact that roughness effects are correlated by empirical relations[17]. Although some investigators have been able to describe some characteristics of rough wall flow[22,35,36], experiment and theory are still far apart. An example of the possible complexity of roughness elements is the study of Ligrani and Moffat[28]. An extensive survey of the effects of roughness elements is provided by Cox[37].

The preceding studies present methods to guide design and placement of a wide variety of turbulent boundary layer thickening devices which preserve the boundary layer structure of the naturally developing boundary layer. The least critical and complicated of all the mechanisms is found to be application of sandpaper to increase surface roughness. This can serve the dual purpose of tripping the laminar boundary layer to turbulent flow and increasing its thickness. Clauser[20] and others maintain that as long as the roughness does not extend above the laminar sub-layer, then similarity of the boundary layer will be preserved and it will obey the law of the wall.. It is possible that this condition would automatically be satisfied for a sand-paper boundary layer trip that extends far enough downstream of the transition point.

## C. DRAG MEASUREMENT

It is possible to measure viscous drag directly or indirectly. Internal flow (pipe) viscous drag in constant cross sections is often performed by measuring pressure loss[10]. In external flow viscous drag forces can be directly measured with a force transducer arrangement[38]. The present discussion will be restricted to methods used in external flows. In force measurement usually a portion of the surface is replaced by an embedded sensor surface, generally about a half inch to an inch in diameter (some non-circular sensors have been used). The surface is directly connected to a small force transducer underneath the surface. It is possible to achieve good results with test sensors, but care must be taken in installation[39]. They must be accurately aligned with the test surface and the machinery must be able to measure extremely small forces. Curiously enough, the gap between the sensor surface and the test surface is not critical. In the case of circular sensor surfaces, an oversized gap between the sensor and the surface can increase the allowable alignment tolerance.

The second basic category of skin friction measurement is indirect measurement. Generally indirect methods are based on similarity arguments and/or certain assumptions about the velocity profile and turbulence level in the boundary layer. The simplest methods are derived from measurements of the velocity profile of the boundary layer, generally with a hot-wire anemometer. If the instrument can take measurements inside the laminar sub-layer, then the skin friction at that point may be determined from the slope of the velocity profile of the sub-layer[17]. This measurement is difficult or impossible to perform under most circumstances, and other approaches are used. If the free-stream velocity is very stable, then it is possible to bracket the desired point of friction measurement on the surface with two measurements of the boundary layer velocity profile. These measurements are some distance apart along a streamline. A simple calculation produces the momentum defect between the two points and the friction coefficient is then interpolated. A very stable free-stream velocity, several data points through the boundary layer, and a considerable length of time are required to determine drag.

If the full velocity profile is measured, further assumptions can be made to determine the friction coefficient, based on knowledge of boundary layers . The method of Clauser[20] utilyzes the logarithmic law of the wall to calculate skin friction. This method requires similar turbulent boundary layer velocity profiles ("similar" since the velocity profiles scale to an identical curve when properly normalized, independent of surface length Reynold's Number). Also, since the logarithmic law of the wall is used, boundary layer data taken in the laminar sub-layer can not be used ($y^+$ less than 20). The outer portion of the boundary layer will also deviate from the law ($y^+$ greater than about 1000 for zero pressure gradient) so this data must not be used. Since the coordinate $y^+$ is determined from the skin friction, some iteration is necessary to fit the data. In the method of Clauser the iteration is obviated by a simple graphical procedure. Since this method has been verified by other studies and since it is based on the similarity assumption, it serves as a means to determine if a similar boundary layer exists. Similarity is very important if results are to be compared to any other study, or if the results are to have much meaning at all.

Allen[39] extends the work of Clauser into compressible boundary layers with the Baronti-Libby compressible boundary layer transformation. Primary emphasis is on computational procedures and a comparison with a Preston tube calibration which is determined to be as good as the Baronti-Libby transformation procedure.

The similarity assumption in turbulent boundary layers also applies to the Preston tube[40]. Use of dimensional analysis and the assumption that the flow close to the wall is mainly determined by the surface stress leads to the conclusion that the velocity near the wall is proportional to a friction velocity (the square root of shear stress over density). The

Preston tube measures the velocity by a miniature impact tube resting on the surface. The velocity or the impact pressure can be calibrated against skin friction by experiments conducted in pipes, where flow conditions can be deduced by other methods. It has been shown that the calibration performed in a pipe is applicable to external boundary layers[40] (boundary layer similarity must still exist in the pipe). The Preston tube and similar devices have had wide acceptance, especially in environments that are difficult for hot-wires and other less rugged sensors[41].

The use of Preston tubes in pressure gradients was explored by Patel[42] and produced interesting results. Limits on the pressure gradient environment for use of the probe were established, and it was found that the 'inner-law' velocity distribution (the laminar sub-layer velocity distribution) breaks down under strong favorable pressure gradients. Patel also determined the exact function for the inner-law velocity distribution. His extensive work is widely used as a basis for other studies involving Preston tubes. However, refinements on the accepted means of calibration are still being made[43].

Perhaps the most indirect method of skin friction measurement is often based on similarity arguments. If the velocity distribution is dependent on the surface shear at the wall, then a small heated area on the surface will lose heat at a rate that is a function of the shear. This assumes, of course, that the heating element and the heat transfer does not appreciably affect the velocity distribution itself. The theory behind such a thermal fluxmeter in shear flow is fairly well defined[44], and has been applied to incompressible adiabatic wall flows. A difficulty arises in applying this type of measurement to turbulent boundary layers[45]. While the turbulent boundary layer has a thin laminar sublayer near the wall, it does differ from a strictly laminar boundary layer enough to produce differences in the calibration. Since calibration of these devices is performed in flows of 'known' wall shear, calibration in turbulent flow will automatically correct for deviations from the laminar calibration theory.

Although the intent of the NASA study was to provide surface drag measurements by several means, including hot-wire, direct surface shear force measurement, Preston tube, and thermal fluxmeter, only the hot-wire was effectively used in the course of the experiment development. Although the hot-wire is capable of resolving friction coefficient in a clean air flow, the experiment would ultimately measure gas-particle flow properties. This requires robust sensors such as the Preston tube and the thermal fluxmeter, which were not used before the conclusion of this study. The surface force measurement does not bear on the main concerns of the study.

## D. HOT-WIRE ANEMOMETRY

Hot-wire anemometers are designed to measure the velocity of gas or liquid flow by heating a thin wire with electric current. The heat transfer from the wire can be related to the fluid flow velocity, as well as electronically measurable qualities of the heated wire. This review is intended to illustrate something of the history of hot-wire anemometry, of progress made in calibration of hot-wires, and of the difficulties encountered in the usual operation of hot-wires. A recent bibliography by Freymuth[46] claims that the entire body of literature of thermal anemometry consists of about 1400 papers, some 200 of which were published prior to 1950. A large part of this literature is concerned with hot-wire anemometry.

There are many reviews and histories of hot-wires published, of which the most recent is a review by Comte-Bellot[47]. Much of this short history which follows is paraphrased from her paper and that of Freymuth. The origin of hot-wire anemometry seems to lie in the last two decades of the nineteenth century. The theory of the convection of heat from a fine wire was based on the work of Fourier, Poisson, Boussinesq, and Ser. Crude attempts at velocity measurements were made by Oberbeck (1895) and Weber (1894) by a heat-transfer device, and it appears that Shakespear was the first (1902) to attempt velocity measurements with a heated wire. The work by King (1915), however, provided a sound theoretical and experimental basis for hot-wire anemometry which stands up well to this day.

For the most part early anemometers were of the constant-current type, with the wire assuming different temperatures and resistances corresponding to the heat-transfer and the velocity of the flow. Due to the elementary state of electronics until the 1950s, a form called the constant-temperature anemometer was not very practical. In this form, the temperature and resistance of the wire is kept constant by means of a feedback system. This system was invented by Morris (1912) and it was first implemented in 1921 (with a commercially available version soon after). Ziegler invented the first constant-temperature anemometer with electronic feedback in 1934. While Ziegler utilyzed his constant-temperature equipment to measure velocity fluctuations in 1934, Dryden and Kuethe had already achieved success with such measurements in experiments with a constant current anemometer with electronic corrections in 1929. Since the basic operation of the hot-wire was established, considerable work has been devoted to understanding the response of the wire and the associated circuitry, and in improving the circuitry and interpretation of hot-wire readings.

A typical hot-wire probe is shown in Figure 3. Most commercially available probes use tungsten wire[48] as the sensing element due to its high tensile strength at high temperatures. This is plated with platinum to provide a means to easily solder or weld the wire to the prongs. This plating is chemically etched from the middle of the wire. Some

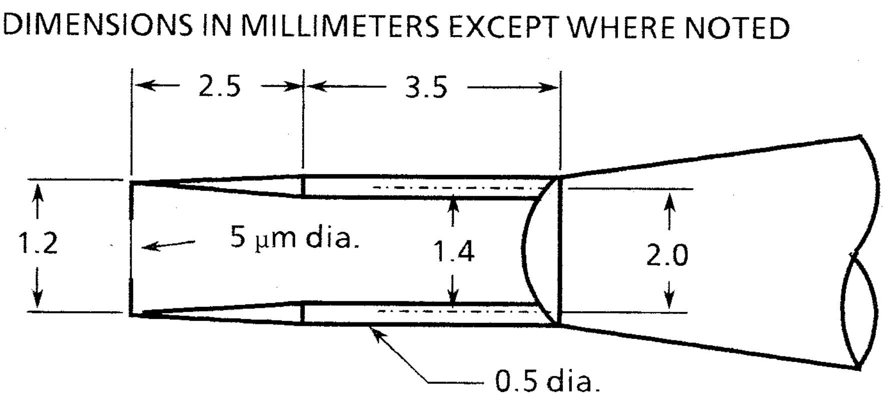


Figure 3 - Typical hot-wire probe, DISA 55.A.25

investigators prefer platinum or platinum-rhodium wires coated with silver[7] on the ends, made through the Wollaston process. The sensing portion of the wire is generally five microns in diameter, which results in a very fragile instrument. Due to the small length of the wire and the size of the supports, the temperature along the wire is not constant[49]. A simple model of the influence of the supports assumes that, because of their greater mass and size, they are essentially at the surrounding fluid temperature. This results in the temperature distribution of Figure 4. A more sophisticated analysis of the thermal influence of the prongs was performed by Perry and Morrison[50]. Their results compare favorably with experiments, and predict dynamic effects well. An important result of the prong 'interference' is that, if the temperature of the hot-wire varies, heat transfer to the prongs will become important and will affect the response of the wire significantly. This

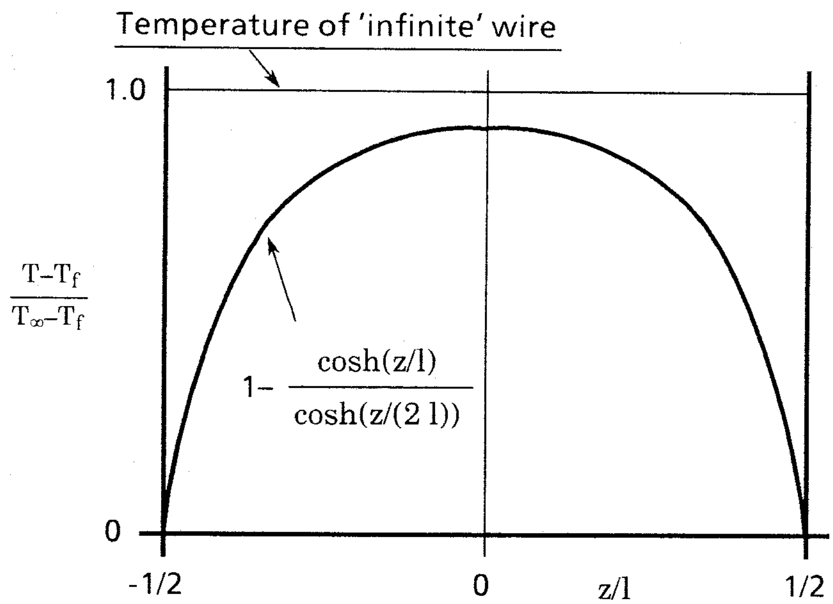


Figure 4 - Hot-wire temperature distribution

variation affects the constant-current hot-wire anemometer, whereas the constant-temperature anemometer, by its nature, avoids the response problem[47]. For flows of appreciable turbulence (turbulence intensity of 0.1% or greater) the constant-temperature anemometer is best, although the constant-current anemometer is still used to measure low-level turbulence because the circuitry does not add as much noise to the hot-wire signal. The present discussion will be restricted to constant-temperature hot-wire anemometers.

One of the most important components of a hot-wire anemometer is the electronic circuitry which provides the feedback and constant-temperature operation of the wire. As the basic system illustrated in Figure 5 shows, a feedback amplifier of some sort is necessary to provide control of the resistance and temperature. Since such feedback can introduce some errors, it is important to recognize the system limitations. An extensive analysis was performed by Perry and Morrison[50] which identifies many of the relevant influences on the system response, and parameters which most influence the performance of the constant-temperature hot-wire anemometer. With the advent of advanced

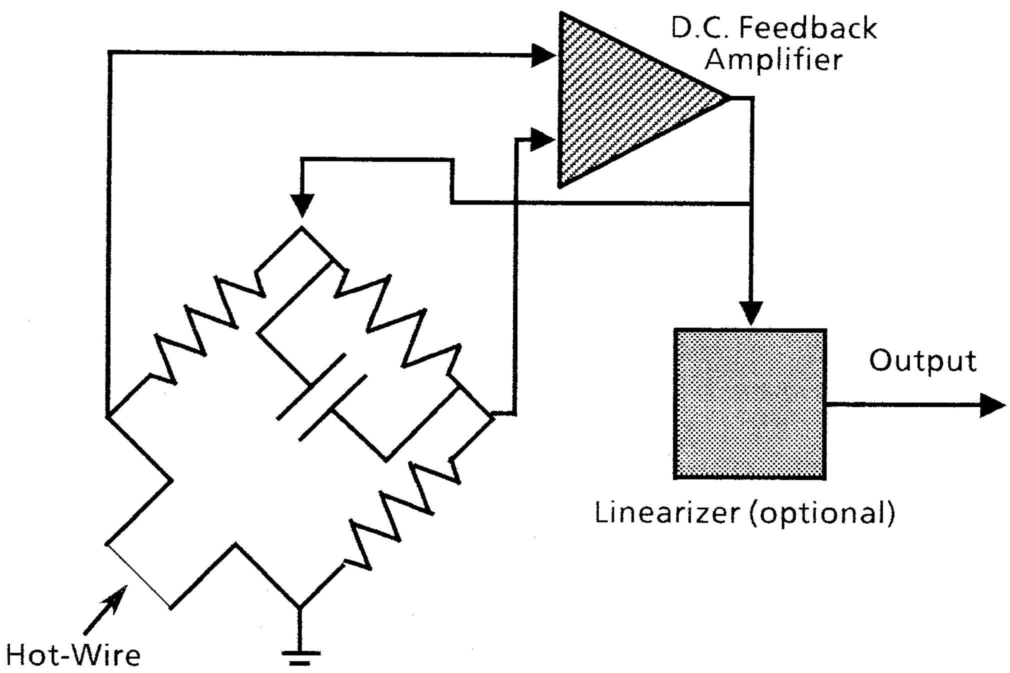


Figure 5 - Hot-wire anemometer feedback circuit for constant temperature operation

integrated circuits, mainly in the form of operational amplifiers, it is now possible to construct anemometer units tailored to the experiment at hand, and with much greater capability than previously available. Miller[51] presents such a design of a simple linearized hot-wire anemometer, and Simpson, Heizer, and Nasburg[52], have refined his unit, providing higher reliability and greater ease of adjustment. However, for most investigators, equipment is limited to commercially available hot-wire systems.

There are many other factors besides the influence of the circuitry and the thermal effects of the prongs that affect the readings of a hot-wire anemometer. It can be seen that the probe itself is mainly sensitive to flow normal to the wire[47]. If the presence of the prongs, probe stem, and support can be neglected, then the wire will respond equally well to flow in the plane shown in Figure 6. Generally the probe is used where the main

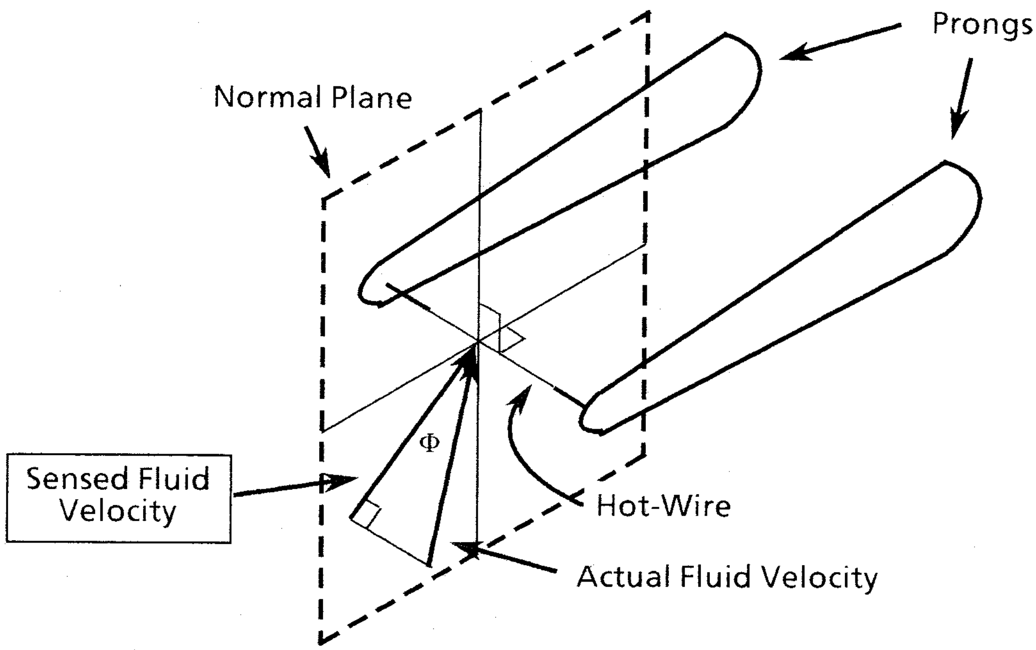


Figure 6 - Fluid velocity direction sensed by the hot-wire

velocity component can be assumed, and other components can be presumed small. However, in high intensity turbulence and/or reversing flow situations this ambiguity is intolerable. Even though the wire basically responds to flow normal to the wire, investigations by Webster[53] have shown the relation to be more like

$$U^2(\Phi) = U^2(0) \times \left( \cos^2\Phi + 0.04 \times \sin^2\Phi \right) \qquad (23)$$

over a wide range of wire aspect ratios. Here $\Phi$ is the angle between the velocity vector and a vector normal to the wire, all three being in the same plane. This relation is different from the normal flow relation by 6% at a flow angle of 45 degrees.

The hot-wire is susceptible to all sorts of complications arising from the thinness of the wire and the fact that it is heated. The most important factors in this regard are oxidation of the tungsten wire and fatigue of the materials[54], causing a change in characteristics of the wire (calibration and strength). Operating life of the probe is shortened due to these factors. Expansion of the wire can cause it to lose its straight shape, as shown by Perry and Morrison[55]. They also proved that significant errors can be created by this expansion, especially if the wire is very distorted by the air stream. In the worst case the wire can rotate in a skipping or whirling mode that introduces very serious errors.

The environment can also have a profound effect on the operation of a hot-wire. The worst problem that can occur is dust contamination or breakage of the probe. Fine particles in the air, driven at the free-stream velocities, are quite capable of breaking the fine wire. If extremely fine particles are present, or vapors of oils or other chemicals, these can stick to the wire and contaminate the surface, changing the heat transfer characteristics of the device. Collis[56] treated the problem of conditioning of the air in wind tunnels to prevent contamination. A secondary problem has to do with the temperature of the fluid the probe operates in. Since the characteristics of the heat transfer are dependent on the temperature difference between the wire and the fluid, any temperature change in the fluid will affect the calibration of the wire. Generally, small changes in environment temperature are ignored when operating the probe at a high temperature relative to the fluid[57].

The environment of the probe is not only the fluid it operates in, but also the objects that surround it. It has been shown that the probe stem and prongs affect the velocity that the hot-wire experiences. Comte-Bellot, Stohl, and Alcaraz[58], treated the subject of aerodynamic interference of single hot-wire probes, and Strohl and Comte-Bellot[59] performed similar experiments with cross-wire anemometers. In both papers, the aerodynamic disturbances were found to be substantial. In the case of boundary layer measurements, where the probe operates close to a lower-temperature surface (at the fluid temperature in low-speed flow), a theoretical and experimental study by Piercy, Richardson, and Winny[60], showed that a correction was necessary to readings close to a surface. Wills[61] carried out experiments which more closely duplicated the boundary layer environment, and achieved similar results.

At this point it is well to note that the probe itself is not without influence on the phenomena being measured. In most cases, lacking better instruments, it is assumed that the probe has only a small effect. However, Tritton[62] has explored this subject in the case of the effect of the probe on the boundary layer. In his experiments, he compared the readings of a single wire reference probe with and without another obstacle in the vicinity, a cross-wire probe. By this means he detected an error in the intensity of turbulence in the boundary layer due to the presence of the extra probe. This effect occurred only close to the surface, and no disturbance in the velocity profile was noted.

The calibration of the probe itself is still in a state of development after many years. There are many factors which affect the performance of the hot-wire and the anemometer circuitry, most so significant that a single theory or equation can hardly give a good account of them. The hot-wire is a non-linear device which is often used for dynamic measurements, and that makes static and dynamic calibration very important for good results.

The earliest substantive work on hot-wire anemometers, by King[63], provides a calibration law which is highly simplified but still gives good results under many circumstances. It is useful for determination of velocity in a fairly restricted range. For the heat transfer due to forced convection King obtained

$$H = \frac{2 \pi \kappa \Theta_0 n \beta_0}{\int_0^{n \beta_0} e^u K_0(u)\, du} \qquad (24)$$

$$2n = \frac{cV}{\kappa} \qquad (25)$$

$K_0(u)$ is a Bessel function

The integral can be approximated numerically with a portion of this equivalent series for large velocities

$$\int_0^x e^u K_0(u)\, du + 1 = \left[2 \pi x\right]^{\frac{1}{2}} \left(1 + \frac{1}{8x} - \frac{1^2 \times 3}{2!\,(8x)^2} + \frac{1^2 \times 3^2 \times 5}{3!\,(8x)^3} - \dots\right) \qquad (26)$$

Taking the first term of the series King arrived at the simplified form

$$H = \kappa \Theta_0 + \left[\pi \kappa s \sigma \beta_0\right]^{\frac{1}{2}} V^{\frac{1}{2}} \Theta_0 \qquad (27)$$

or, for general calibration

$$E^2 = A + B V^{\frac{1}{2}} \qquad (28)$$

where the constants A and B are found from a least-squares fit of the calibration data. In general this data is obtained from comparison to a pitot-probe or from a special calibration device[57]. The heat transfer of the heated wire is equal to the electical power dissipated through the resistance. In a constant-temperature anemometer the wire is operated at a constant resistance and the electrical power is proportional to the square of the voltage across the wire.

In the 1950s many investigators tried to refine the perception of heat transfer from fine wires. Apparently one of the most widely accepted studies today was produced by Collis and Williams[64]. Their careful study was concerned less with a heat transfer 'law' than with some of the basic mechanisms of the heat transfer, and resulted in an exponent law derived from dimensional analysis and experimental data. Their exponent relation is

$$E^2 = A + B V^n \qquad (29)$$

where the exponent is dependent on Reynolds number and is given by the following table:

| Reynolds Number | n |
|---|---|
| 0.2 - 44 | 0.45 |
| 44 - 140 | 0.51 |

In the work by Collis and Williams, the Reynolds number of the wire is based on the wire diameter and the film temperature, an average of free-stream fluid temperature and the wire temperature. In low-speed flows the exponent 0.45 is used. The use of dimensional analysis and experimental data, however careful, still left the matter of the exponent law open to interpretation, as many other works were published proposing different exponents over various ranges of Reynolds number. Of these, it is worthwhile to note the article by Bradbury and Castro[65], in which the authors tried to resolve the differences between the work of Collis and Williams and that of Davies and Fisher. This article, published in 1971, found that the results of Collis and Williams seemed to be more accurate. Other relations besides exponent laws were explored, and several of these proposed expressions for heat transfer from heated cylinders are presented by Hatton, James, and Swire[66]. Of particular note is the function proposed by van der Hegge Zijnen as presented by Hatton.

$$\mathrm{Nu} = 0.35 + 0.5\,\mathrm{R}_{ef}^{0.5} + 0.001\,\mathrm{R}_{ef} \qquad (30)$$

This is claimed to apply to a Reynolds number based on film temperature and wire diameter of 0.1 to $10^5$.

The preceding studies of heat transfer of cylinders, unfortunately, do not address some of the characteristics of hot-wire anemometers in particular. Hot-wire anemometers are subject to end effects, which are avoided in studies of convection by the use of very high aspect ratio wires. Hot-wire anemometers are often used to measure dynamic phenomena such as turbulence, while convection studies are conducted under the most static conditions possible. Since the 1950s, however, the characteristics of ordinary hot-wires have been studied under dynamic conditions. So far the results are mixed. The studies by Perry and Morrison[50] involved shaking a hot-wire probe in a steady stream or inserting the probe in a von Karman vortex street. Their interpretation of data is based on an exponent law static calibration to apply in the dynamic situation, so their conclusions may be influenced by their choice of static calibration method. The work of Kirchhoff and Safarik[67] attempted to produce a dynamic calibration without recourse to any assumed static calibration for interpretation. Their results showed that King's Law is a poor dynamic calibration, and thus of limited use in turbulence measurement. Bruun[68] explored dynamic calibration more thoroughly with respect to the static calibration laws. He found that a good static calibration was essential for an interpretation of turbulence intensity, and that the dynamic calibration would correspond to the static calibration in that case with negligible error. However, it was also shown that any exponent law (of which King's Law is a subset) provided poor static calibration over a large velocity range. Bruun proposed a universal tabulated function for both velocity and sensitivity of the probe as well as relating the function

$$E^2 = A + B\,V^{0.5} - 0.015\,V \qquad (31)$$

This is essentially the same function proposed by van der Hegge Zijnen, with a different constant for velocity to the first power.